ECL 168A

DESIGN AND DEVELOPMENT
BELLOWS RESTRAINT UNIT (A)

General Background

The story demonstrates different philosophies of design arising from the backgrounds and experiences of various individuals, design groups, and companies; it illustrates within one field of work the orthodox and creative approaches and the circumstances which led to each; it shows the use made of testing equipment, of development through prototypes, of buying out parts or complete units, the use made of technical papers, and many other aspects.

This case was written by P. J. Booker, A.M.I.E.D., and appeared in the *Engineering Designer* (Reference 10). It is reproduced by permission of the author; edited for the Engineering Case Program by G. Kardos; published with support of the National Science Foundation.

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General Background

The tender for the Trawsfynydd nuclear power station, which had been submitted to the Central Electricity Generating Board, was accepted in August, 1959. Work began on site almost immediately and from thereon design and procurement had to be fitted into a time table, the first reactor and associated plant being planned to go on load in October, 1963.

The Gas-Cooled Graphite-Moderated Reactor

The first atomic reactor was constructed in America during World War II. It consisted of a pile of graphite blocks built up into a rectangular prismoidal form with a number of horizontal channels for taking the uranium fuel.

When Britain considered commencing an atomic energy programme in 1945, it seemed imperative that this should be based upon natural uranium as a fuel, and two moderators then seemed possible—heavy water and graphite. A moderator was necessary to slow down the products of fission to a velocity suitable for them to promote further fissions. Heavy water being expensive and slow in delivery, the British team chose graphite, especially as an air-cooled graphite-moderated pile had been successfully operated at Clinton, U.S.A.

Sufficient uranium and graphite for two reactors was procured and construction of GLEEP, of about 100 kW output was commenced at Harwell in 1946, to be followed shortly by BEPO, of about 6000 kW designed heat output. Atmospheric air cooling was adopted for the latter as it offered the least complication in producing such a reactor quickly.

In 1947 the virtues of finned fuel elements with gas cooling were recognised and it was decided that reactors cooled with atmospheric air could be made to yield plutonium for military purposes at the required rate and sooner than by adopting other possible systems. Two reactors were then built at Windscale, being effectively super-BEPOs.

When thoughts turned towards the production of useful power from atomic energy, one obvious line to follow was that of developing the atomic pile, of which a considerable amount of knowledge had been accumulated. The basic idea was to recirculate the air or other cooling fluid round a closed circuit, so that the heated gases passed from the reactor to a heat exchanger, where heat would be given up to turn water into steam, and then returned to the reactor for further heating and recycling. Providing that the steam was hot enough and gave sufficient pressure, it could then be used in much the same way as steam produced by more conventional means. Recirculation was necessary, of course, otherwise the heat held by the gases emerging from the heat exchanger would be lost.

Simple as this fundamental concept was, it posed a vast number of sub-problems. Be-

cause of the radio-active nature of power by fission, the heat-exchanger and much other equipment had to be completely separated from the reactor, the latter being virtually embedded in thick concrete known as a biological shield. The reactor and heat exchanger, in consequence, had to be connected by pipes or ducts so that the coolant could flow in circuit through both. The fluid flowing in these ducts had to be as hot as general design conditions would allow in order to get a reasonable thermal efficiency. Apart from the temperature, there was also the matter of the quantity of heat to be transported. Some liquids were considered but whilst these are good conveyors of heat they are, in general, strong neutron absorbers compared with gases and could lead to a reactor never reaching criticality unless enriched fuel were used. In the end, carbon dioxide gas was selected because it was the best which could be obtained sufficiently pure in bulk at a reasonable cost. The choice of a gas coolant meant that it had to be used under fairly high pressure in order to cope with the quantity of heat. Indeed, since at any time there are limits to the size of heat exchangers and ducts which can be built, and because beyond certain speeds of gas flow the pumping power requirements become excessive, to handle the quantity of heat it became necessary to have a number of heat-exchangers and duct systems connected to the reactor vessel.

Using a gas under pressure made every part of the circuit effectively a pressure vessel. The maximum pressure which could be used depended mainly on: (a) how small the reactor, and so the enveloping pressure vessel, could be made, and (b) the thickness of steel plate which could be safely and confidently welded to form the pressure vessel.

In the original studies it proved easier to support a reactor and pressure vessel in the upright position than in the horizontal, so that the horizontal fuel channels were replaced by vertical ones. This led also to the present layout of vertical heat exchangers and ducting in vertical planes.

The Problem

In the preliminary layout of the ducts for Trawsfynydd, hinge-pin type bellows restraint units had been specified, the size and properties of these being assumed from units known to exist. When the time came to investigate the possibilities of procuring bellows units, one of Atomic Power Constructions' associated Companies, Richardsons, Westgarth & Co. Ltd., still had some available capacity and they suggested that they might submit a tender. R.W.G. had never tackled restraint units of this size before, but like so many other firms dealing with such units, there was a considerable experience of designing and manufacturing flexible ducting on the gas- and steam-turbine scale. Since the criteria were simply that a suitable design of unit should be available at the right time and price, it was agreed in January, 1960, that R.W.G. should be given the opportunity to submit a design of restraint unit, and a first technical meeting was called at which, in effect, a preliminary specification was given.

One of the important points to emerge was that any restraint designed by R.W.G. should be comparable in length to those postulated in the duct layout. This was about 5 ft., a figure based upon the shortest hinge-pin unit currently believed to be available. The shortest unit was chosen in the first instance because this led to a more compact ducting arrangement

and thus a more compact building. A great many decisions affecting the ducting, the building and the arrangement of other equipment had already been taken, and an increase in bellows unit length would have necessitated quite uneconomic changes. A preliminary figure for tolerable bending or restoring moment for full deflection was also given, as well as ducting size, gas temperature, pressure and other necessary data.

Work was started at R.W.G. immediately. At this time four consortia were well advanced with first generation nuclear power stations. Whilst these had been written up extensively in the technical press, the emphasis was mainly on the nuclear aspects rather than on the incidental engineering. Whilst a bellows restraint unit is important—as is everything in a design—it is still a "detail" with respect to the whole station. The information was meagre and approximate.

Large Gas Ducts

The problems which arise in designing large gas ducts for nuclear power stations stem from a number of different and often conflicting requirements which fall broadly into the following categories: (a) taking up the thermal expansion of the ducts and vessels, (b) ensuring leak-tightness and the strength of the ducts as pressure vessels, and (c) minimising the power required to move the gas round the circuit.

The maximum stress in the pressure vessel shell is made up roughly of two components; stress due to internal gas pressure, and stresses at branch flanges or nozzles due to bending moments or other forces transmitted by the ducts through expansion or other causes. If the ducts raise very high stresses at the nozzles then the gas pressure of the system has to be reduced until a safe overall stress level is obtained.

For an efficient system, therefore, the ducts should produce minimum loads at the points where they enter the pressure vessel and heat-exchanger and this is accomplished generally by making the ducts flexible. In 1950, there were two main ways of making ducts flexible. Both had been developed for heavy industrial gas turbines and had grown out of previous steam turbine and plant practice. The first method was to utilize the bends in the ducting to give inherent flexibility; corrugations were then often introduced into the duct material in the vicinity of the bends to reduce stiffness and so increase flexibility, Fig. 1(A). The other method was to introduce virtually "pin joints" at certain points so that the ducting could move on "mechanism" principles.

About the latter, Feilden wrote in 1958:

"In industrial gas turbines, a very important objective is to obtain what, for want of another word, has become known as "kinematic" construction. When this term is applied to gas turbine ducting components, it indicates that a design is used in which temperature variations are accommodated without the development of the very large thermal stresses which might occur if a rigid attachment were used. A simple example of ducting of this type is shown in Fig. 1(B), which may be regarded as a completely flexible system, within the limits of the maximum permissible deflections of the three metallic bellows used in it. Though bellows are sometimes used to accommodate axial movements in pressure pipework, it was decided to restrict their movement in this gas turbine application to

one of flexure, which would keep the stress in the bellows at a low value. The problem was then to carry the substantial end-loading due to the internal pressure in the duct, which in this design amounted to about 4 tons. In one of the bellows (A) a simple trunnion mounting was used, which only allowed the bellows to flex along the axis of its pivots, and took up the longitudinal expansions in the horizontal pipe (B), or in the parts to which it was connected. To ensure a fully kinematic construction, gimbal rings were used to carry the end loads developed in the two remaining bellows (C), and these gave a characteristic analogous to a ball joint–i.e., freedom of flexure in all directions, but complete restraint of axial movement.

"When approaching the design of these gimbal rings, the first step was to calculate the end loading and then to consider how this would be carried by a gimbal ring. The first attempt was to treat the ring as a beam in bending, which suggested that the most appropriate section to adopt would be a rectangular one with an axial length considerably greater than its radial thickness. Luckily, the precaution was taken of making up a specimen of a bellows and its gimbal ring, and carrying out a pressure test upon it, which showed that the axial expansion under working conditions was no less than a quarter of an inch–which, from every point of view, was completely unacceptable. Chastened by this result, a model of the gimbal ring was made in the drawing office in thin card, and when the load on the pins was simulated by two pieces of bent welding wire, it immediately became obvious that the ring was deflecting very substantially in torsion, due to the couple between the two sets of pins. In retrospect, this is perfectly obvious and when once the point was recognised...."

The alternative method mentioned by Feilden, in which expansion is taken up by axial movement in the bellows is illustrated at Fig. 1(C). Here the pipework is supported in guides which allow axial movement while the bellows compress to accommodate the expansion in the pipe sections. This is an appropriate method for small scale work or when pressures are low, but as each section of pipe is free except for the bellows connection the end loads due to internal fluid pressure have to be taken on anchors–and these loads grow rapidly with increases in duct diameter and pressure.

In the Calder Hall nuclear power station, which might be considered as the prototype for subsequent stations, the size of duct settled upon was 4 ft. 6 in. diameter constructed of 3/8 in. plate to hold a gas pressure of 100 p.s.i. The layout of this ducting is shown in Fig. 3. At the time no information was available on the manufacture or behaviour of large corrugated type ducts, especially how they might behave over long periods; in consequence, the only reasonable solution to the problem of giving the ducts flexibility for thermal expansion was the kinematic one using tied bellows.

As with the pressure vessel and duct-work, convoluted bellows have stresses arising from two causes; the internal pressure of the gas giving hoop stress and, added to this, stresses due to bellows deflection. To keep the overall stresses in the bellows as low as possible, the deflection from the neutral position was halved by pre-stressing the bellows in the cold condition in the opposite direction. In practice this meant

artificially contracting the duct-work—or giving it a "cold draw"—and this was effected by closing each section of the circuit with a piece of ducting specially made to template. The early stages of heating then lowered the bellows stresses by moving the bellows to the neutral position; further heating then took them beyond this point and stressed them in the opposite sense. This has, naturally, become standard practice.

Calder Hall Gas Ducts & Bellows Restraint Units

From a special issue of the Journal of British Nuclear Energy Conference published in 1957 and devoted to Calder Hall, was the following:—

"The principal problems associated with the large 4 ft. 6 in. dia. gas ducts . . . were those concerned with maintaining a leak-tight system and ensuring sufficient flexibility so that despite the very considerable expansion differentials involved, the loads and moments on the reactor vessel, heat exchangers and circulators to which they were connected, were kept to very low limits. At the same time the pressure drop in the system had to be kept to a minimum.

"The general design was based on roughly comparable conditions experienced in large gas-turbine installations where most expansion problems between two points could be covered by the introduction of a bend with three sets of bellows units tied against end pressure and hinged to permit flexing. The ducting is considered as rigid links with the joints at the bellows units, the angular rotation at the joints being a function of terminal displacement of the vessels (due to expansion and differential settlement) and expansion of the duct lengths themselves. Where flexibility is required in more than one plane in a circuit, a gimbal type of bellows construction is used. All circuits were constructed to Lloyd's Class 1 requirements.

"...The problem of carrying the concentrated end load of approximately 150 tons for the design pressure of 125 lb./in.^{2} gauge from the pins to the flanges in such a way as to prevent distorting stress concentrations, demanded much thought. Model tests were made on several possible solutions, and in the design which was finally evolved an axially split and bolted casing completely containing the bellows proper was spigotted to the flanges, thus serving to distribute the highly concentrated pin loads more or less uniformly round the flanges. Note that the casings were stiffened circumferentially at the joints to avoid undue deflection of the hinge pin and so remove the possibility of its seizing. The bellows pins are of nitrided steel in lead-bronze bushes."

The pins were lubricated with molybdenum disulphide grease.

This restraint unit is illustrated in Fig. 2.

Commercial Nuclear Power Stations

Calder Hall having served as a successful prototype, British industry began to organise itself for the purpose of designing and constructing commercial nuclear power stations. A number of consortia were formed and these eventually tendered for the first orders from the Central Electricity Generating Board.

The A.E.I.—John Thompson Group began work on the Berkeley station and the

Nuclear Power Plant Co. Ltd. started on the Bradwell station. Shortly afterwards the G.E.C.–Simon-Carves Atomic Energy Group won the contract for the Hunterston station (Scottish Electricity Generating Board), while the English Electric–Babcock & Wilcox–Taylor Woodrow Atomic Power Group undertook the design and construction of the station at Hinkley Point. The G.E.C. Group also won the contract for a station at Tokai Mura in Japan, and the N.P.P.C. similarly undertook the building of a nuclear power station in Italy at Latina. Somewhat later Atomic Power Constructions Ltd. were formed and they, in due course, were awarded the contract for the Trawsfynydd station in Wales.

Since there are a very large number of variable parameters to settle and much information becomes available with the passing of time, naturally the detailed layouts of these power stations differ considerably, though all have basic similarities founded upon the Calder Hall prototype. The general arrangements of pressure vessels, ducts and heat exchangers for one circuit, somewhat simplified, are shown in Fig. 3 for some of these stations.

In 1960 the A.E.I.–John Thompson Group and the N.P.P.C. went into partnership to form The Nuclear Power Group, and they started work on the construction of a second generation station at Dungeness. The English Electric Group also started work on a second generation plant at Sizewell and, to complete the picture, A.P.C. and the G.E.C. Group went into partnership as United Power Company Ltd.

Whilst there will be changes in future stations due to the use of prestressed concrete pressure vessels, all the stations depicted in Fig. 3 are very similar, although there are successive improvements over time. All the first and most of the second generation stations use "kinematically" designed ducting incorporating tied-bellows units developed within each Group by different design teams. It is not possible to make any direct comparisons between these different restraint units, partly because insufficient information has been released, and also because each design had to be made to suit the requirements and properties of a particular duct layout. Many of the designs are separated in time and in the intervening periods there were continual increases in gas pressures from 125 to about 300 p.s.i. and in gas temperatures from 350 to 410^{o}C. Duct diameters also increase from 4 ft. 6 in. to 6 ft. 6 in. The situation was dynamic rather than static and the various units produced are not interchangeable.

Published Information on Large Bellows Restraint Units

The Nuclear Power Plant Co. Ltd. gave the job of developing suitable bellows restraint units for the Bradwell station to C. A. Parsons & Co. Ltd., who had previously worked on the Calder Hall units and which was a member Company of the Group. Subsequently a Paper was published in which the following is recorded:

"(The Calder Hall hinge-pin type) of construction was not adopted for the Bradwell bellows because it was considered to have limited development prospects owing to its high cost and the tendency of this cost to increase rapidly with size. The design chosen incorporates a simple flexible tongue the ends of which are welded into

the adjacent ducts. A central cross-brace is provided at each end of the tongue to ensure that the tongue remains plane when flexed. In order to provide protection against the catastrophic consequences of a tongue failure under pressure, each bellows units has two tie rods attached to brackets at each end of the unit. These bars are normally unstressed but they are designed to take full gas force in the event of a sudden brittle failure of the tongue. Their proportions have been so chosen that they dissipate by slight yielding the work done by the gas force. This device substantially reduces the stresses in the stiff brackets to which they are attached. (See Fig. 4).

"A disadvantage associated with the use of a tongue for tying a bellows is that the joint has no fixed centre of rotation. This does not lead to any difficulties where the bellows joint is deflected purely by a couple with no shear-type forces at right angles to the plane of the tongue. Shear forces can impose large extra deflection stresses on a bellows. These stresses are highest for the convolutions at each end of the bellows and are additive algebraically to any existing stresses in these convolutions due to rotation of the joint. This difficulty with shear forces can easily be overcome by the addition of a light pair of hinges on the centre line of the bellows. These hinges do not carry any axial load but are subject to a small lateral load which at Bradwell would not exceed five tons. The effect of shear forces is very small in the majority of bellows at Bradwell and hinges are unnecessary. In the three joints where they could be used with advantage it was decided that on balance it was cheaper to use a somewhat larger number of convolutions than to equip a small number of bellows with hinges."

In the authors' reply to the discussion, Dr. A. T. Bowden and Mr. J. C. Drumm said that they were fully appreciative of the fact that an internal tongue restraint was not a universal solution to the general problem.

"...They were very conscious of the limits of the field of applicability of the design, particularly those associated with the use of that type of restraint for temperatures significantly higher than the 400 to 420°C figure which was common to the current generation of civil reactors in Britain. They were aware that it was possible to design a hinged restraint which would give perfectly satisfactory service in a reactor gas circuit. The same could also be said of restraints which relied on the use of two or four external tie bars, externally mounted flexible tongues, or rolling action by a pair of interlocking hinge pieces mounted externally on the axis of rotation of the bellows. During the preparation of the design of the Bradwell station those various alternatives had been examined and the conclusion had been reached that for the particular conditions prevailing in the gas circuits of that station a flexible tongue restraint would represent a solution to the bellows problem which was at once simple, adequate for the duty and cheaper than competing designs."

A fair amount of development work was necessary and the Paper recorded some of this together with information on the various tests carried out. Quoting from the Bowden and Drumm Paper:

"The final design adopted for the Bradwell bellows tongues was chosen after a number of tensile and bending tests had been carried out on tenth-scale models. These model tests showed that longitudinal tension in the tongue gave rise to an area of

severe stress concentration in the region of the inboard ends of the welds which connect the tongue to the duct wall. It was decided to reduce the magnitude of the local peak stress in this region by using 2½ in. thick plate with a central flexible portion which is machined down to 1½ in. thickness. Peak bending stresses occur at the ends of the flexible length. It will be noticed...(Fig. 4)...that these ends have been kept well inboard of the areas of stress concentration close to the tongue welds...

"Strain gauge readings taken during a pressure test on a prototype 60 in. bellows to four times design pressure indicated that the magnitude of the stress concentration factor at the weld ends was 7.... At one time it was hoped that by suitably profiling the edge of the tongue it would be possible to reduce this high stress concentration factor. However, a series of ten tests on models with different fillet radii showed that a substantial reduction in the stress concentration factor could not be achieved along these lines.

"In the early stages of the design of the gas circuit from Bradwell it was decided to build a full-size bellows joint and to subject it to an extensive series of tests with a view to proving the suitability of this type of bellows for service in the coolant circuit of the reactor. It was also hoped that the tests would provide useful data on which to base future designs."

Very little information concerning comparable hinge-pin types of bellows restraint units had been published at this time, but some interesting views were aired in the Discussion and Communications attached to the Bowden and Drumm Paper. For instance, Mr. J. J. Haftke of Babcock & Wilcox Ltd. said,

"...the authors had stated the basic requirements which the tying device should fulfill as being absolute reliability, a small resisting moment and the absence of need for maintenance or lubrication over the life-time of the plant. It could well be argued that in a design for which long-term operating experience was not available, it could not be certain that maintenance or repair would not be required at some time. It was perhaps truer to say that the tying device incorporated in the Bradwell bellows was incapable of being maintained, if by maintenance was meant a procedure aiming at slowing down the rate of normal wear and tear deterioration. The more conventional design of restraint, incorporating a hinge pin carrying the full load, so far as could be predicted—and there was a considerable volume of experience available—should not require any maintenance during the life-time of the plant. Should, however, that prediction prove optimistic, such maintenance would be quite a simple operation by comparison with that which would be involved if the Bradwell type of restraint were to show signs of deterioration earlier than expected.

"In addition the ability provided by the hinge pin design for the periodic examination, during shut-down, of the pin surfaces and of testing their freedom of rotation seemed to be a very significant advantage. It would be quite unjustified to place similar faith on the value of periodic inspection in the case of the tongue-type restraint where the signs of trouble which would be looked for would be cracking of a nature which could well pass unnoticed in any non-destructive examination...

"The limitations of the hinge-pin type of restraint were presumably not as imminent as the authors believed at the time of the design of the Bradwell bellows, since they had been successfully developed, for instance, for the Hinkley Point power station where the duct diameter was 6 ft. 6 in. and the operating pressure was in excess of 200 lb./in.^{2}. It was also quite apparent that these conditions by no means represented the limit of capability of that type of simple restraint."

Mr. V. Westermann of Engineering Appliances Ltd. commented,

"Perhaps the most serious objection to the flexing plate...appeared to have been dismissed far too lightly in his opinion. That was the lack of any fixed centre of rotation. The authors had commented that it did not lead to any difficulties where the bellows joint was deflected purely by a couple with no shear type forces. In a complete ducting system he thought that there would be very great difficulty in eliminating all forces of that nature, and with that type of unit, light restraining hinges would appear to be essential. With the existing arrangement there was no certainty about which axis the bellows would bend, or even that the bellows would tend to bend truly rather than take up a combined offset and bending position. There was also no resistance to any turning moment which might tend to twist the bellows radially about the axis of the unit...The machining and placing of the tongue became a precision operation incompatible with the general 'plumbing' attitude inevitable in any large duct-work where working accuracies of 1/8 in. were extremely good. The use of the bending plate also led to a great overall length; an equivalent hinged unit would only be approximately 5 ft. long. The authors' unit would appear to be 8 or 9 ft. long at least.

"The only advantage of the bending plate would appear to be the constant moment obtained throughout its life, although that might be affected by corrosion or radiation on the bending plate. His practical test figures using hinges were nevertheless very similar to those of the authors, a 5 ft. 6 in. unit pressurized to 230 lb./in.^{2} and deflected through one degree required a maximum moment of about 500 ton/in. to deflect... After 5000 movements that figure was reduced to less than half that value."

To round off this series of pros and cons, the following is taken from the authors' reply:

"The mode of flexure of such bellows (in the particular case) could be predicted with sufficient accuracy... It was quite true that the torsional stiffness of the tongue was low compared with that of the bellows. In carefully erected uniplanar duct-work...there were no torsional forces present which were likely to give rise to significant stresses in any but the most fragile bellows. They would point out that hinged restraints were by no means immune to the failings mentioned by Mr. Westermann. Because of the clearance at the hinge pins and the transverse flexibility of the hinge arms, a considerable portion of the transverse forces present in a duct line would be taken by the convolutions of a bellows . . . They would also suggest that the usual designs of bellows hinge gear made but a small contribution to the overall torsional stiffness of a hinged bellows."

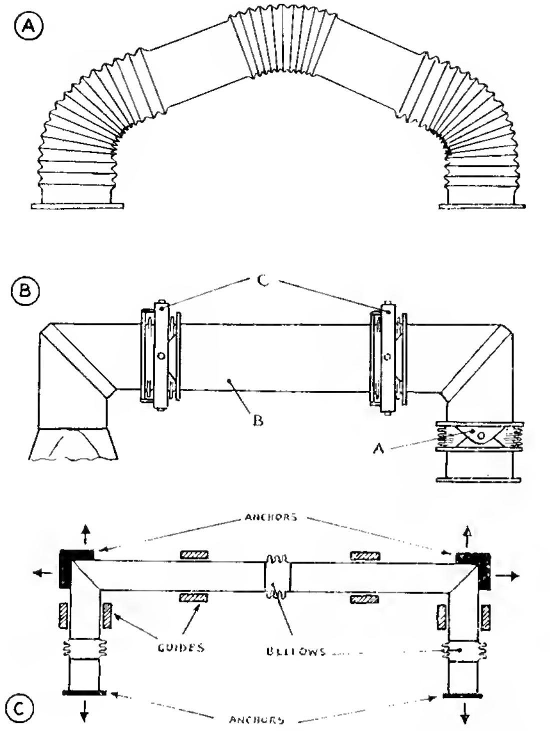

Fig. 1. (A) Inherently flexible gas ducts with corrugations at bends. (B) Full "kinematic" gas ducting as used on industrial gas turbines. (C) Bellows used to take up axial movement due to thermal expansion, with end loads taken on anchors.

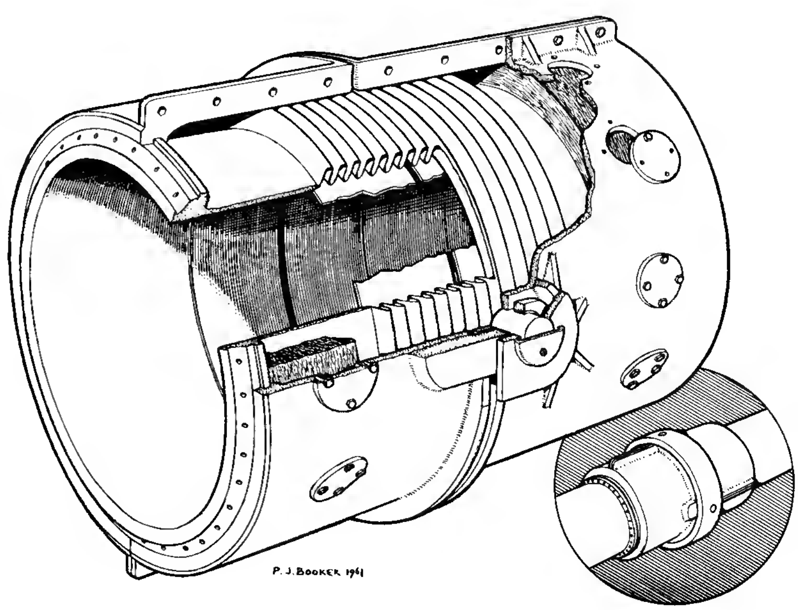

Fig. 2. Hinge pin type of restrained bellows joint developed for Calder Hall nuclear power station gas ducts. The diameter is 4 ft. 6 in.: the end load is about 150 tons resulting from internal gas pressure of 125 p.s.i. The inset shows a modified version with gimbal ring for universal movement.

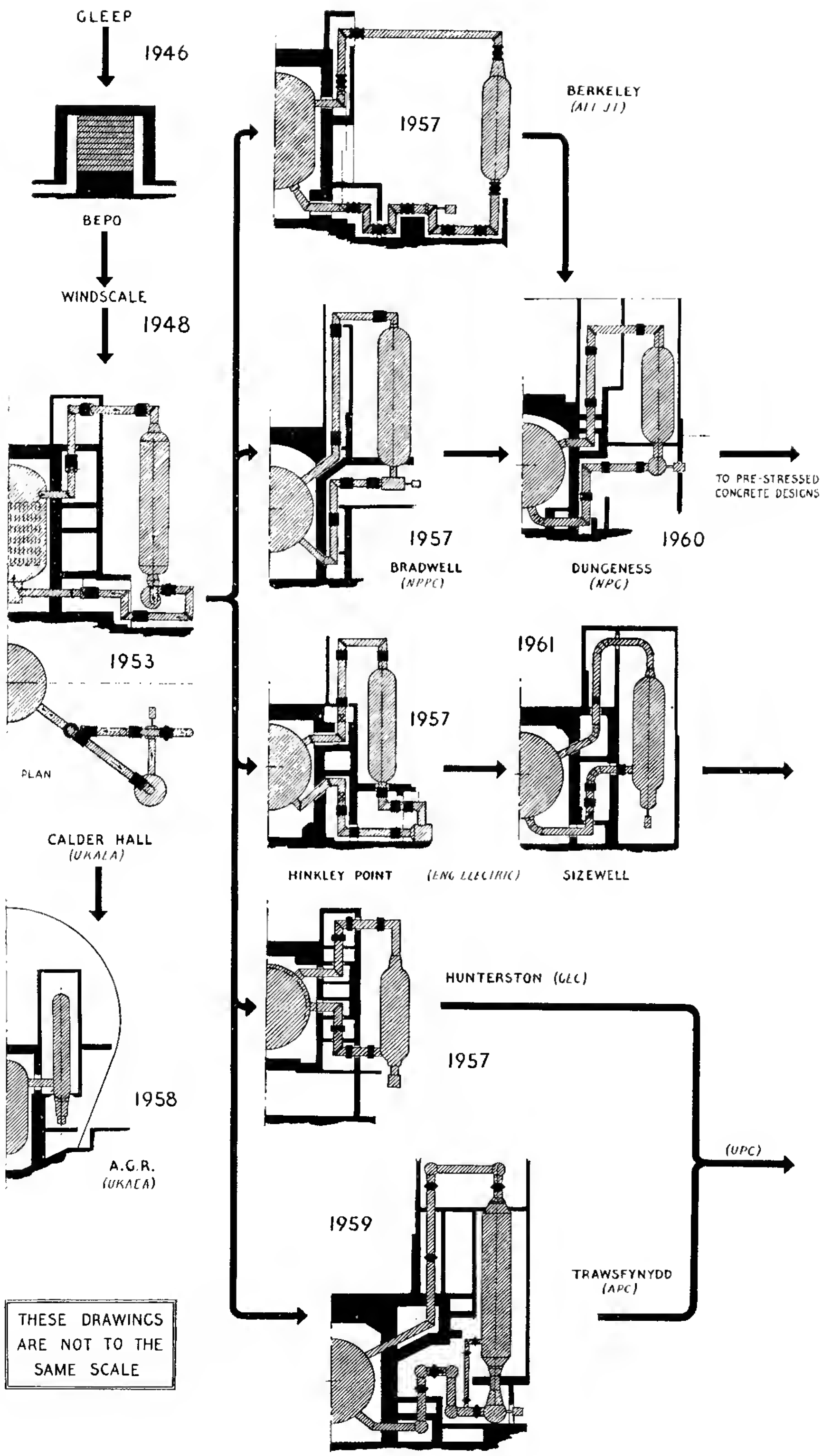

Fig. 3. Family tree showing the development of gas-cooled, graphite-moderated reactors for power generation.

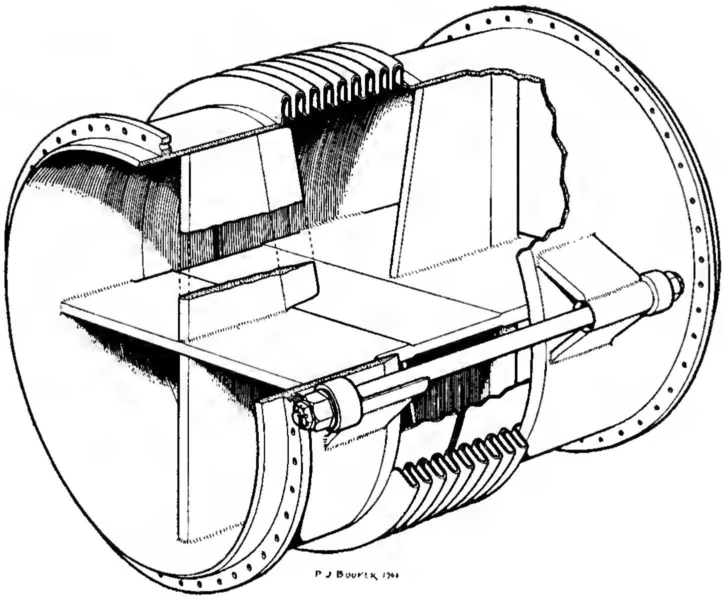

Fig. 4. Flexible tongue bellows restraint unit developed by Parsons for the Bradwell nuclear power station gas ducts. Diameter 5 ft.; end load about 220 tons from gas pressure of 140 p.s.i. The design of individual units varies somewhat according to their positions in the duct circuits.

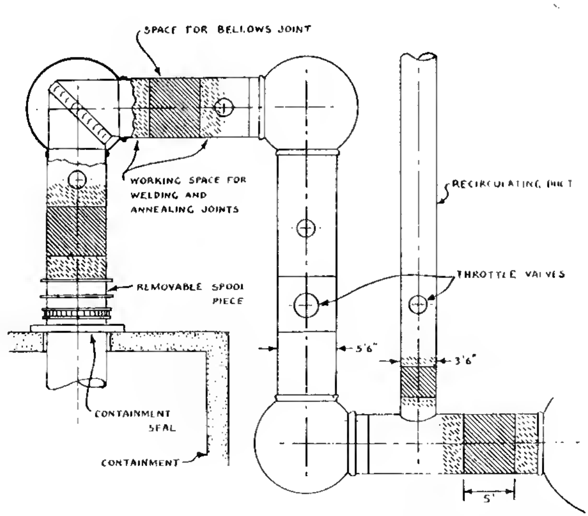

Fig. 5. Section of Trawsfynydd ducting, showing position of bellows in the cool duct. The spherical elbow bends were designed parallel to the restraint units by the same team and were not shown on early duct layouts.

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DESIGN AND DEVELOPMENT
BELLOWS RESTRAINT UNIT (B)

Initial Ideas

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Initial Ideas

Whilst it seemed to be technically possible to produce a suitable hinge-pin unit, it was almost a foregone conclusion that the development work necessary would make such a unit costly and not competitive with models already available from companies with some years' experience. (Fig. 6–Solution 1). It seemed better, if possible, to design a unit which was not in direct competition with nearly identical units. In other words, if development was necessary, as seemed likely, the time and money thus spent should be on some new design which had a further development potential.

Apart from the hinge-pin type, a second precedent was also known of, namely, the Parsons' flexible tongue restraint designed for the Bradwell station. This unit had been developed for a 5 ft. diameter duct with a nominal gas pressure of 140 p.s.i. The Trawsfynydd units would be for 5 ft. 6 in. ducts with a nominal gas pressure of 240 p.s.i. Allowing for fault and other conditions, the end loads for the two cases would be about 200 and 450 tons respectively. Calculations were put in hand for a preliminary assessment of a flexible tongue design. To take the higher gas pressure a somewhat thicker tongue would be required for the higher tensile load. To keep the additional bending stresses low enough, a larger radius of curvature would be needed, leading to a longer tongue for a given deflection angle—say, about 3 ft. No calculations were carried out on the difficult stressing problem of anchoring the tongue, but using the Parsons' unit as a guide it seemed likely that 2 to 3 ft. would be necessary either side of the tongue. The idea was, therefore, considered unfeasible for a unit less than 8 or 9 ft. in length. (Fig. 6–Solution 2).

In the meantime, thrusting out for new ideas, the Chief Designer had put forward the idea of a unit working on torsion instead of bending. Preliminary sketches were made and calculations showed that the idea was probably feasible for the project in hand. The torsion bar would be under complex bending and shear loading as well as torsional loading, and this was not considered to be an ideal solution, particularly as it would probably have little development potential. (Fig. 6–Solution 3).

After digesting the results of these preliminary investigations, two further ideas were put forward. One was a modification to the flexible tongue solution, aimed at reducing the length of tongue required; this was put forward, naturally enough by the engineer who had made the flexible tongue calculations. In this proposal, the tongue would be replaced by two tongues one above the other each half the thickness of the single tongue (Fig. 6–Solution 4). The tongues would be pre-stressed by bending them slightly in the opposite sense. During deflection, one tongue would bend more, building up bending stress but being partly relieved of tensile stress, while the other tongue straightened out, taking more of the tensile load while being relieved of bending stress. This would allow the tongue length,

and so that of the whole unit, to be shortened. Preliminary calculations showed that the idea was probably feasible; on the other hand, the anchoring and correct pre-stressing of the tongues might present difficulties.

The Chief Engineer suggested as another idea the possibility of using a conical lattice of rods. The precedent for this was rather remote and the similarity was only apparent when viewed at a high level of abstraction. Some years previously, when the Chief Engineer and Chief Designer were working on a gas turbine design, during testing a peculiar unpredicted mode of vibration occurred on a shaft as in Fig. 6(A). Investigations led them to the conclusion that the frusto-conical shape of the casting holding the shaft was the cause. In simplifying calculations, this had been replaced by an "equivalent" cylindrical piece. However, the behaviour of the frusto-cone turned out to be rather different from that of a cylinder. Whereas a cylinder behaved similar to a beam, the frusto-cone tended to "side-slip," so that up and down movement of the bearing also caused an angular movement. This is demonstrated in (B) and (C) by pin-jointed links. The actual distortion of the frusto-cone, exaggerated, is shown in (D). In other words, whilst in the axial direction the frusto-cone had the same properties and rigidity as an equivalent cylinder, this shape had another property of being able to side-slip, causing an angular movement. The small angular movement of the shaft was recognised to be similar to that required on the duct joint.

The abstract frusto-conical surface was replaced by a number of suitably arranged rods and these were initially considered inside the ducting, effectively replacing the tongue or double-tongues. The novelty of the arrangement, however, posed a number of problems, mainly on account of their being so many variables—the length and angles of the rods could be varied, as well as the number and diameter of the rods. (Fig. 6–Solution 5(a)).

Like the tongue case, each rod would need to take a tensile load plus a bending stress. Initially, to keep the tensile stress down, the small angle of 25° was assumed. Within the overall length limitation this appeared to give rods of a reasonable length, which seemed desirable to keep bending stresses low. Taking 1 in. diameter rods and conventional stress values, etc., preliminary calculations showed that this arrangement called for about 60 rods in each conical frustum. The bending moment of these rods in rough calculations appeared to be very low, being only a fraction of the maximum allowable bending moment for the complete unit. The rods and central anchorage would offer an obstruction to gas flow and would be inaccessible. However, the solution in principle appeared to be eminently feasible with a wide margin for development.

The gas flow objection could be overcome in the obvious way by placing the conical lattices on the outside of the duct. The circular anchorage where the cone bases met would be considerably larger and heavier, but this seemed to be a small price to pay for a completely free bore and for ease of accessibility. (Fig. 6–Solution 5(b)).

The possibilities of this new idea were such that preliminary drawings for a prototype were embarked upon. Stress calculations

based now upon a more definite arrangement, showed that a 25° cone angle was reasonable but that rather longer rods were desirable to keep rod stresses low. It was soon seen that this could be done by making the two conical lattices interpenetrate one another. Indeed, by this device it seemed possible to shorten the unit length below 5 ft. if necessary. (See Fig. 6–Solution 5(c)).

At this stage, far more attention had to be given to the design of the rods and this fell into a number of categories–such as stressing, fixing, manufacturing methods, and so on, each affecting the others to a greater or lesser extent.

When a rod is used as a beam, generally the load is known and the deflection varies according to the dimensions given to the beam. In this case a rod is used in such a way that the deflection is known and the force necessary to give this deflection–which shows up in the whole unit as the bending or restoring moment–is dependent upon rod shape and size. Another criterion is the maximum stress level in the rods. Both restoring moment and stress were calculated very approximately when judging feasibility of this idea; however, at that time nominal stress levels assuming static deflection were assumed, and the arrangement was too loosely defined to work out any reliable figures.

What should be the maximum allowable stress in the rods? This was a difficult question. These restraints would be virtually stationary for long periods, but Bowden had estimated that they would move through at least 240 full deflection cycles in a 20-year life. Each unit would also have to be tested with a number of full deflection cycles under pressure. The conditions were thus ones in which fatigue was of importance, although the variations in stress through movement might be widely spaced in time. Fatigue conditions mean lowering the maximum stress level from what would be permissible in static conditions, but whilst fairly reliable figures were available for cases of millions of reversals, no data was available for only a few thousand reversals–besides which generalised data of this kind tends to become unreliable in this range. Some reasonable assumptions had to be made taking into account the method of manufacture, surface finish, and so on, specimen rods later being put to the test.

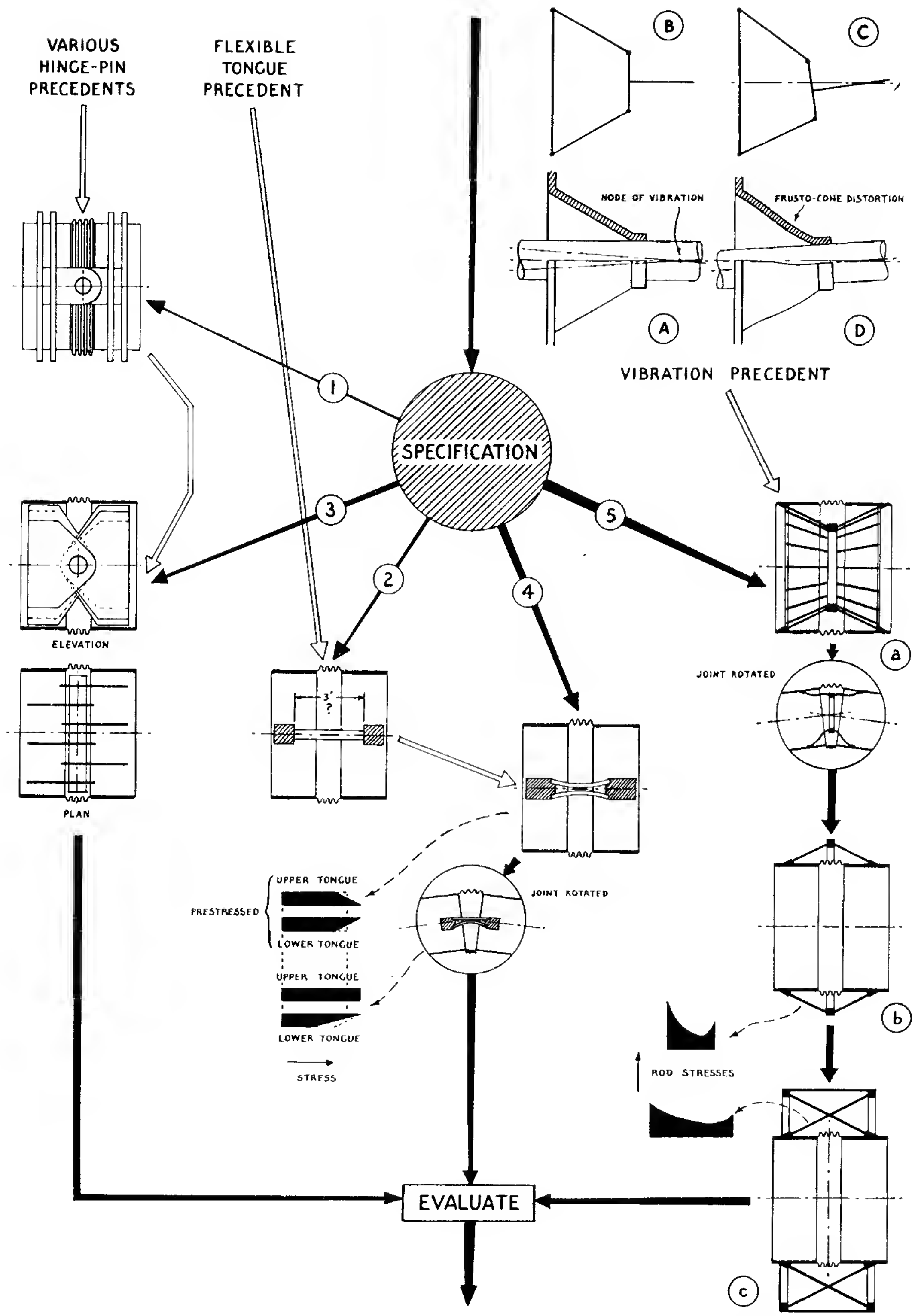

Fig. 6. The solutions considered, their derivations, relationships and development.

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ECL 168C

DESIGN AND DEVELOPMENT BELLOWS RESTRAINT UNIT (C)

Prototype

DESIGN AND DEVELOPMENT
BELLOWS RESTRAINT UNIT (C)

Prototype

The stressing of the bellows restraint tie rods was not as straightforward as might at first sight appear. The rods would be in tension to take the gas end load, giving them a basic stress. The rods would also be bent, effectively as two cantilevers joined together, giving an additional bending stress. There was yet a third effect; the tensile load acting through the bent rod would naturally tend to straighten it, an effect which increased the bending moment at the anchors–increasing both the bending moment of the whole unit and increasing the maximum stress which occurred at the anchorages. It soon became apparent that 1 in. diameter rods would give excessive stresses and bending moments. Instead, three times as many rods, each with one-third cross-sectional area, were postulated–180 rods of 0.6 in diameter. The maximum stress at the rod ends could be further reduced by increasing the diameter at the ends; every postulated change of this kind, however, altered the rod deflection shape, the bending moment and the stress levels.

In the meantime, the overall form of these rods could not be decided until the method of fixing was known and the method of manufacture.

Some of the detailing stages are demonstrated in principle in Fig. 7. If the rods were looked upon statically the arrangement in (A) seemed fair enough in principle. However, examination of the whole arrangement showed that only the first one or two rods could then be fitted. In general the rods would have to pass through the annular ring to be fitted. So (A) was modified to (B), providing a nut at both sides, the remainder of the rod being such that the inboard nut could be fitted. This arrangement also had to be modified, of course, to provide means of turning the rod so that the thread at the other end could be screwed home, to provide means of locking the nuts, to give the necessary clearances and so on, as in (C).

Because of its shape and because a uniform tensile strength was required throughout, machining from bar seemed to be called for. On the other hand, the fatigue conditions, as yet unassessed, suggested that a surface free from machining marks would be advantageous. R.W.G. engineers were, however, familiar with "Newallastic" studs, used in other fields of design, which were cold rolled and particularly fatigue resistant. Although a tie rod was very much longer than any known stud of this kind, this method of production seemed worth investigating and an enquiry was made to Messrs. A. P. Newall & Co. Ltd.

The process of producing "Newallastic" studs and bolts is essentially one of cold hammering or swaging heat-treated and ground alloy steel in rotary machines, which reduce the stud or bolt shank to a size slightly below the root diameter of the thread. The reduction in the shank diameter, of course, increases the length of the stud, so that fine control of the process is necessary. The surface produced by swaging is extremely smooth and entirely

free from tool marks, while a certain amount of compressive stress is retained, due to cold working, which is beneficial in providing fatigue resistance. The threads are rolled on circular die machines and this again produces threads of great strength.

The properties of cold swaged studs were just what were wanted in the tie rods, although the length of the latter, some 42 in., and the amount of reduction were somewhat greater than anything previously dealt with. As mentioned earlier, there was a considerable overlap of the various aspects affecting the design of these tie rods and, in fact, at the time Newall's engineers started working with those of R.W.G., the actual number of steps and their diameters had not been finalised, since this was as much a matter of what could be manufactured as what was theoretically desirable. It was finally decided that the rods should be made in a 75-ton steel and should be reduced at each end in three steps, one to below thread root diameter, followed by two further reductions.

Even so, the actual production of these rods presented a number of problems to Newall's engineers. Because of their length, an extension of about 14 in. took place during the processing from the original blank to the finished product, and to maintain the accurate swaged lengths on each operation, special limiting devices had to be incorporated in the machine feeds and the whole technique almost completely reversed from that normally employed. Furthermore, where a very long swaged portion was required—as was the case with these rods—extreme care had to be exercised to maintain an accurate and constant diameter, as a deviation of as little as 0.005 in. would result in quite a considerable difference in the length of the swaged portion and so of the whole rod length.

After a number of experiments had been made, suitable rods were produced and, in the words of Newall's Technical Director, "....quite a considerable amount of credit is due to the machine operators themselves, who showed tremendous enthusiasm and skill in producing what proved to be a first class job."

Naturally, all the other parts of the prototype arrangement had to be progressed through similar stages to finalise the form of each, and each of these parts provided further problems to production staff and so on.

In the meantime, as soon in this process as the general form became clear enough, R.W.G. submitted preliminary drawings (approx. Fig. 8) to A.P.C. with an estimated price and a meeting was called to assess the position. Since the tender had been drawn up, some particulars of two comparable bellows restraint units had been published—the flexible tongue type in the Bowden and Drumm paper and a tie-bar type in some technical journals. The very existence of these as well as the arguments put forward by their designers raised doubts about the suitability of hinge-pin type units for such critical application. Very few units had, in fact, been tested at that time for conditions comparable to those which would exist at Trawsfynydd. The Parsons and A.E.I. units were far too long to accommodate. Furthermore, commercially there was something to be said for a unit produced within the Group's own Companies. At this stage the design appeared to be promising and R.W.G. were

asked to go ahead with developments on condition that restraint units could be supplied eventually at a cost comparable to that of alternative units, and it was agreed to produce a prototype for testing by the end of May, 1960.

When the first rods arrived from Newall's, tests showed that these had rather better strength than might have been anticipated and, as the holes had not then been drilled in the prototype under construction, the number of rods was reduced by a third to 120 in each lattice. A special test rig had also been designed and built for fatigue testing these rods, and the fatigue properties of the specimen rods turned out to be so good that in assembling the prototype the number of rods was again reduced by a quarter to 90, by simply omitting every fourth rod. (Fig. 8A).

A suitable convoluted bellows had been procured from Teddington Aircraft Controls (Bellows Division) and, as far as possible, calculations were made to predict the bending moment of the complete restraint unit. The bending moment of the bellows was known and the moment of the conical lattice of rods could be predicted fairly closely as a result of the calculations already made and from experiments on single rods. A comparatively unknown quantity, however, was that concerned with the "pumping action" of the unit, a function of the change of enclosed volume when deflected. Whilst some estimations had been made, so far this had been given little attention as any change in volume, especially for a very small deflection, would undoubtedly be small. However, even shortenings of the order of thousandths of an inch when working against a gas load of 450 tons could give a not insignificant component to the overall bending moment.

If one imagined the rods pin-jointed at their anchors, one could predict a small shortening as a property of the geometry. However, the rods were not pin-jointed and it was difficult to tell whether such calculations were significant or not. Again, the bending of a rod would cause its two ends to approach one another by a very small amount and this would probably be reflected in a shortening of the unit, although by how much was difficult to tell. Some simplifying assumptions had to be made, though in making these the very smallness of the changes in lengths led to difficulties in assessing the order of importance of various effects. However, upon the assumptions made a preliminary figure for bending moment due to "pumping action" was arrived at. Whilst this was higher than might have been anticipated, there was a fair chance that the properties of the prototype would fall within the limits of the specification.

The prototype having been completed to time, tests were put in hand. In the main these were tests for strength and safety undertaken to prove feasibility to the insurance authorities, A.P.C. and the ultimate customer, the C.E.G.B. Apart from pressure tests, etc., the prototype was moved through 1250 full deflections under pressure and temperature, and a further 1250 full deflections under pressure. A number of other tests were also carried out in the interests of gaining a fuller understanding of the new design's properties.

One of the first tests was to measure the overall restoring or bending moment with the unit under full pressure and this turned

out to be rather higher than expected—nearly twice the calculated value. This was of some temporary concern as the provisional figure for allowable bending moment in the specification had been reduced by about 20%.

It seemed that the trouble probably was to do with the "pumping action." The method by which this action's effect on restoring moment had been derived was, therefore, re-examined. It became apparent that some of the effects previously considered to be of a secondary nature were probably as important as other effects, and a new method of calculating this component of bending moment was worked out. The values then arrived at for the prototype were very close to the measured value of restoring moment. A difficulty then arose; the new calculations were based upon the predicted shortening of the unit. It was possible that some of the high bending moment recorded was due to structural effects. These, however, could not be isolated since, unpressirised, the measured bending moment due to the rods would be smaller than when in tension, whilst, pressurised, this component of bending moment would be added to the "pumping action" component. However, the actual change of volume of the unit could be measured. The restraint was accordingly filled with water and the change of volume upon deflection ascertained by measuring the overflow. These measured values tallied within a few percent of those calculated and the revised restoring moment theory was thus considered to be sufficiently accurate for prediction purposes.

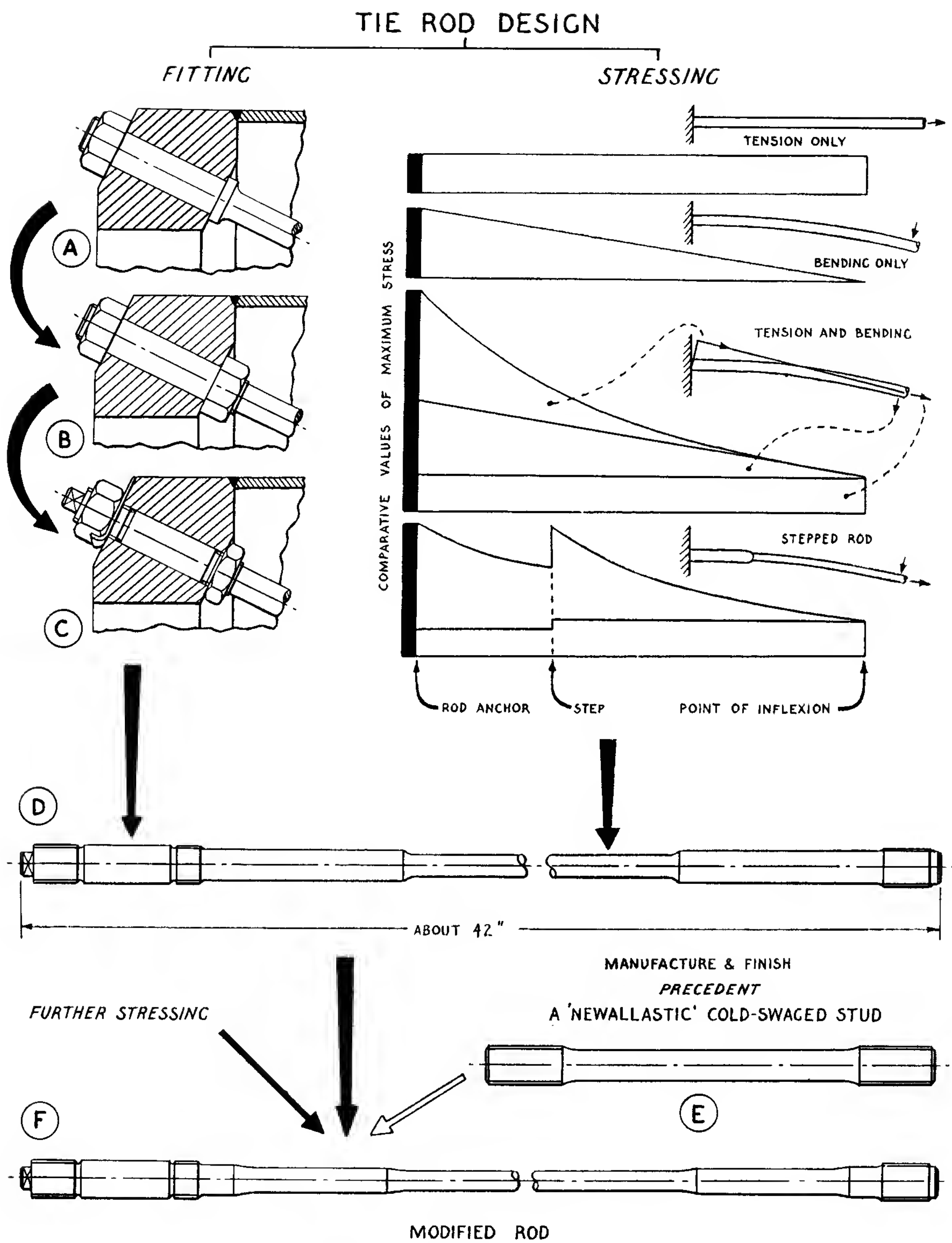

Fig. 7. Simplified stages in the design of the frusto-conical restraint tie rods.

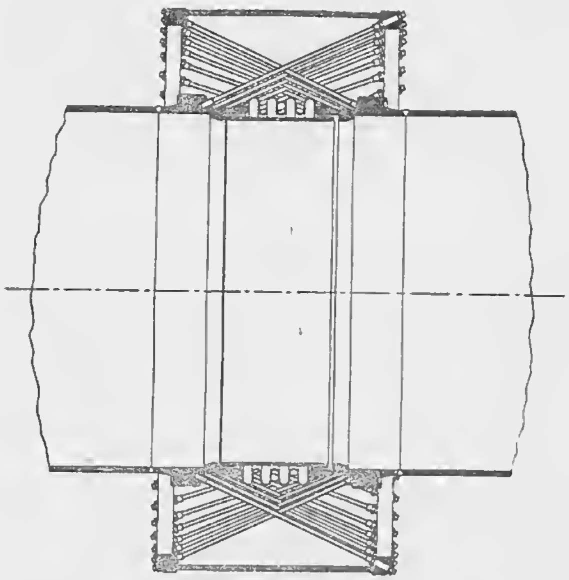

Fig. 8. Drawing of prototype bellows restraint unit. Diameter 5 ft. 6 in.; end load 420 tons from gas pressure of 240 p.s.i. At this stage only "a bellows" is shown, no particular make or kind having been chosen.

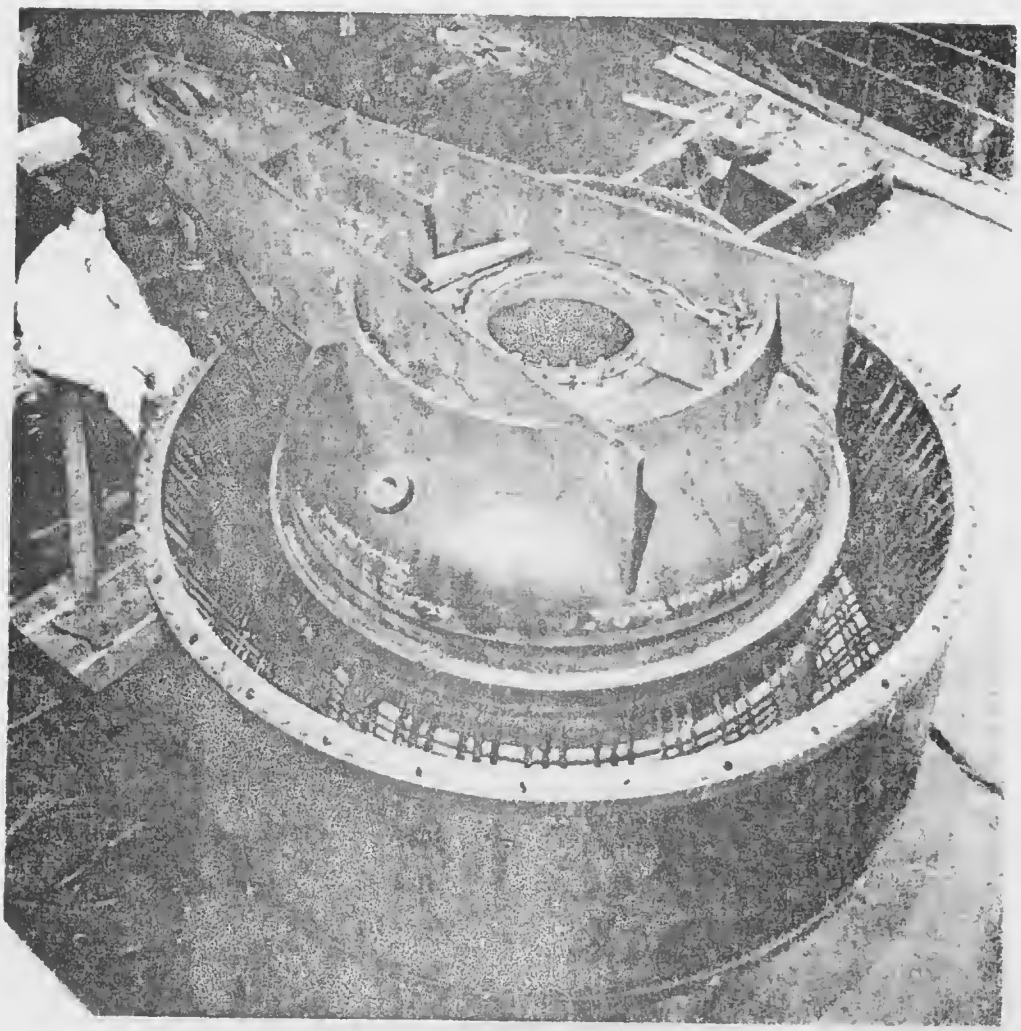

Figure 8A. Photograph of Prototype on Test. Note omission of every fourth rod.

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ECL 168D

DESIGN AND DEVELOPMENT BELLOWS RESTRAINT UNIT (D)

Revised Design

DESIGN AND DEVELOPMENT
BELLOWS RESTRAINT UNIT (D)

Revised Design

Whilst the total restoring moment of the prototype was excessive for the project in hand feasibility had been proved and the final theory of restraint shortening was capable of analysis and of showing the effects of the variable parameters. At the start when stress levels were considered of paramount importance, a small cone angle and long rods seemed desirable. An analysis of the new theory, however, showed that shortening of the unit, now an important criterion, was a function of rod length, of the ratio of rod length to cone apex distance and the cone angle—all interrelated. So, for overall bending moment considerations, the rod length was decreased and the cone angle increased to 50°. To counteract what would otherwise lead to higher stress levels, the number of rods was again increased to 120. These alterations changed the overall properties of the unit, reducing the total restoring moment well within the specified value, whilst leaving the rod stresses very little different from those in the prototype.

These changes in geometry made interpenetration of the frusto-cones unnecessary and new drawings (Fig. 9) incorporating the revised layout were produced and submitted to A.P.C. with a quotation.

It was appreciated also that some minor shear and/or torsion loads might fall on the unit and that the arrangement of rods in itself was inadequate to transmit these across the restraint (i.e., prevent their falling on the bellows). It was, therefore, proposed to replace the one inner sleeve with two sleeves (similar to those shown in Figs. 2 and 4) and to arrange interlocking dog-teeth where they met.

Reports of the tests having been examined by the C.E.G.B. and the insurance authorities, and the design principles having been approved, A.P.C. engineers got down to the job of examining this new restraint layout in terms of its suitability for incorporation in their duct system. The design as a whole had a number of useful properties. The bore was clear for uninterrupted gas flow; there were no mechanical movements; the flexing elements were external; and the joint was universal, equivalent to a gimbal ring hinge-pin unit. The latter property, whilst not essential in this case, was a very useful one, as slight errors in the positioning of ducts, etc., would have a minimum effect. By this time the duct design had advanced to the stage where it was possible to estimate fairly closely the shear loads likely to fall on to these units. The worst case was occasioned by the thrust of the recirculation ducts and the figure for shear load appeared to be higher than that for which the dog-teeth arrangement would be suitable.

This was pointed out to R.W.G.; the figure given for anticipated maximum shear load was, to them, surprisingly high and it soon became apparent that the dog-teeth arrangement would be inadequate in this particular case. The inner sleeves were only to be fabricated from light plate, easily distortable under heavy load. A light pair of hinges could be added which would give

a centre of rotation but without carrying any of the end load. This seemed, however, to be inelegant in comparison with the main design and there was not a lot of space available. A simple, general solution was called for which, amongst other things, would retain the universal property of the joint.

Having had success so far with flexing rods, it was suggested that this problem might be similarly solved. The frusto-conical lattice, viewed at a high degree of abstraction, was simply the use of rods, which were inherently stiff along their axes but flexible in bending, to resist some forces but not others. The idea, then, was to synthesize another arrangement of rods to give the desired properties. Shear and torsion had to be resisted in a plane—so that rods were considered lying in this plane (Fig. 10). They had to be suitably anchored to the duct ends and allow of normal joint rotation. Various arrangements became possible, and the most appropriate one to emerge was to use four rods lying in the centre plane perpendicular to the unit's axis, one end of each rod being attached to one duct end and the other to the other duct end, as shown in Fig. 10 (and Fig. 11). This idea had to be developed, of course, through stages very similar to those detailed for the lattice rods, etc.

At a meeting with A.P.C. engineers the final design incorporating the additional anti-shear modification was examined and approved, and in July, 1960, R.W.G. were given the go-ahead for design and production. It is recorded that "detailed design and testing proceeded"; however, this covered a great deal of work. For instance, the anti-shear modification had to be translated into a suitable hardware form and specimen rods and brackets had to be designed, made and tested. More attention had to be paid to every piece of detail, bearing in mind that though the prototype was available as a precedent it had had to serve only for a few weeks whilst the production units would have to last for years. Corrosion and many other factors had to be considered in the choice of materials in juxtaposition and provision had to be made for fixing lagging to the units. The flanges in the production version and the annular ring were considerably different from those of the prototype and called for different production methods, and so on.

Parallel with the designing of the main production units of 66 in. bore, of which 72 were required at Trawsfynydd, another design for a similar unit of 42 in. bore was put in hand for the recirculation ducts, 36 such units being required. Whilst this followed closely the main design, many of the parameters, apart from size, had to be altered to give different amounts of deflection and different restoring moments. The two units are shown for comparison in Fig. 11.

Whilst the two designs continued to develop, everyone concerned had necessarily to keep reviewing the designs as a whole and in detail as time went by and more information came to light, to ensure that so far as was humanly possible nothing had been overlooked or forgotten. Modifications were made from time to time, sometimes suggested by test results, sometimes as the result of reappraisals of previous work. For instance, the bellows chosen was of the type using equalising rings; tucked away amongst the published communications with the Bowden and Drumm paper were

the following remarks:

"...the need for equalising rings between the convolutions... Very careful dirt exclusion would also be necessary as the presence of a hard particle within the equalising rings would tend to damage the bellows material..."

Whatever the source may have been, eventually someone queried whether there was a possibility of dirt getting between the equalising rings and the bellows convolutions, and if so whether it could lead to premature failure. No positive answer could be given, but it was considered to be a risk not worth taking, so a modification was made to the design in which the convoluted bellows were covered within an aluminum foil envelope.

The final design was approved both by the C.E.G.B. and the insurance authorities. Tests were carried out on the pre-production unit in June, 1961, when the design was satisfactorily proved, and the first production unit was completed on 3rd July, 1961.

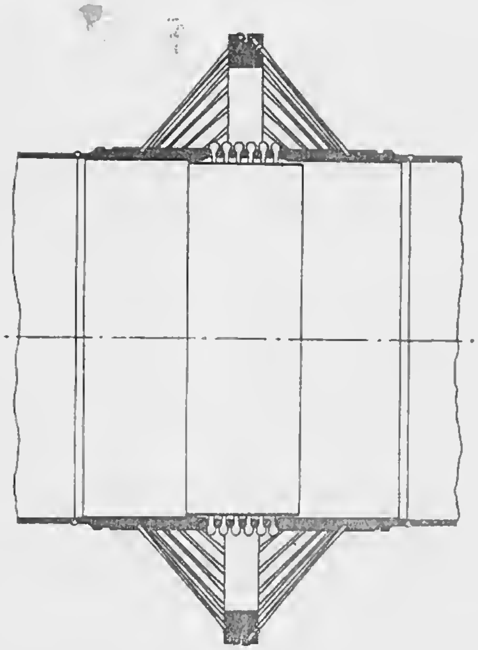

Fig. 9. Drawing of revised restraint design, omitting proposed internal dog-teeth arrangement to transmit shear loads.

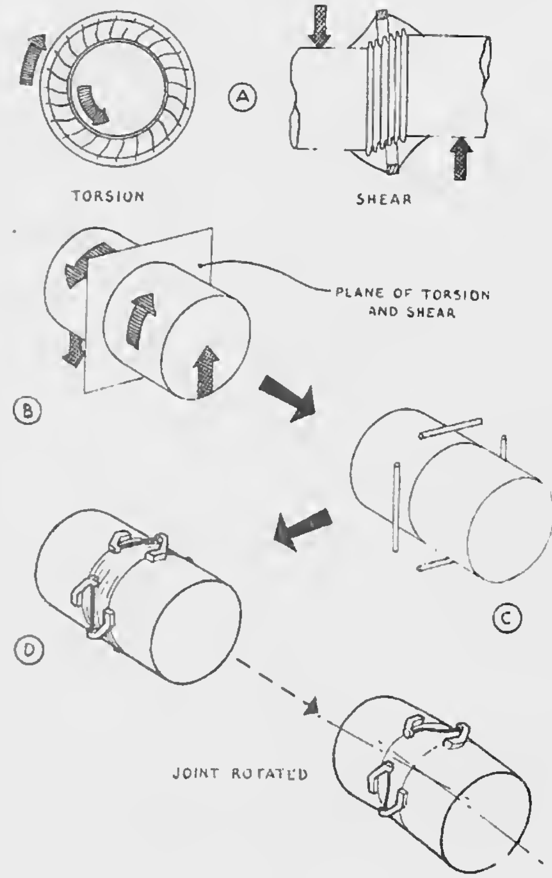

Fig. 10. Effects of torsion and shear on frusto-conical lattices and arrangement of rods for Anti-Shear Units. (See also Figs. 11 and 12).

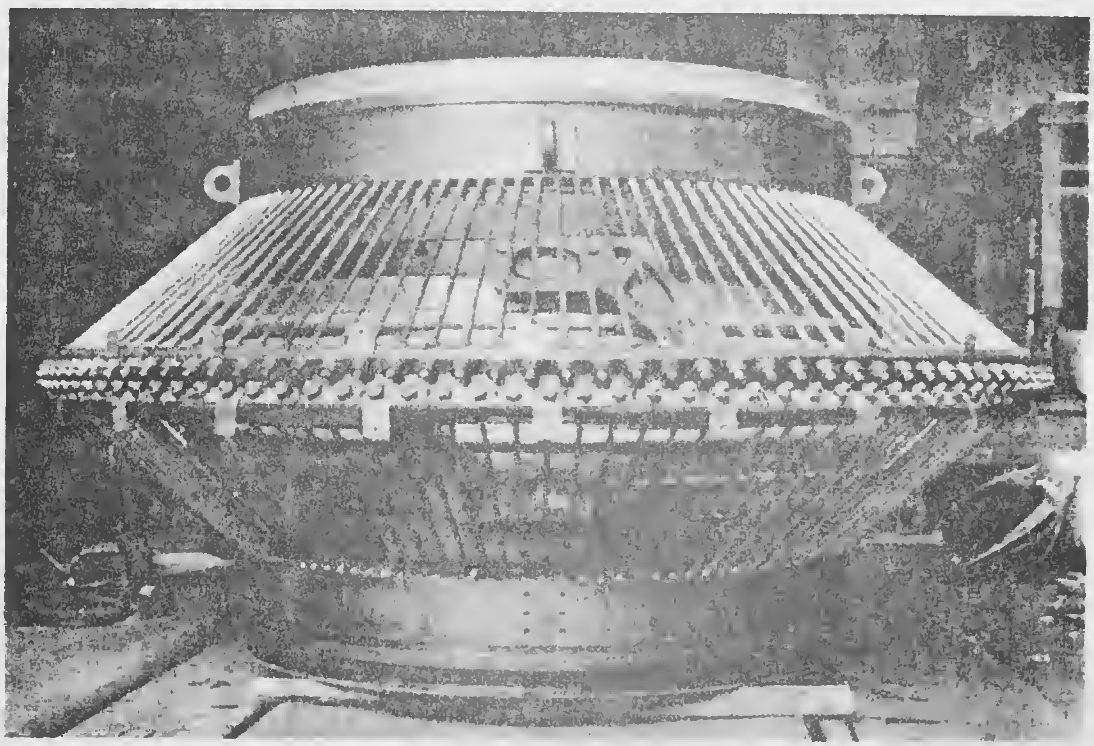

Fig. 12. First Production Unit.

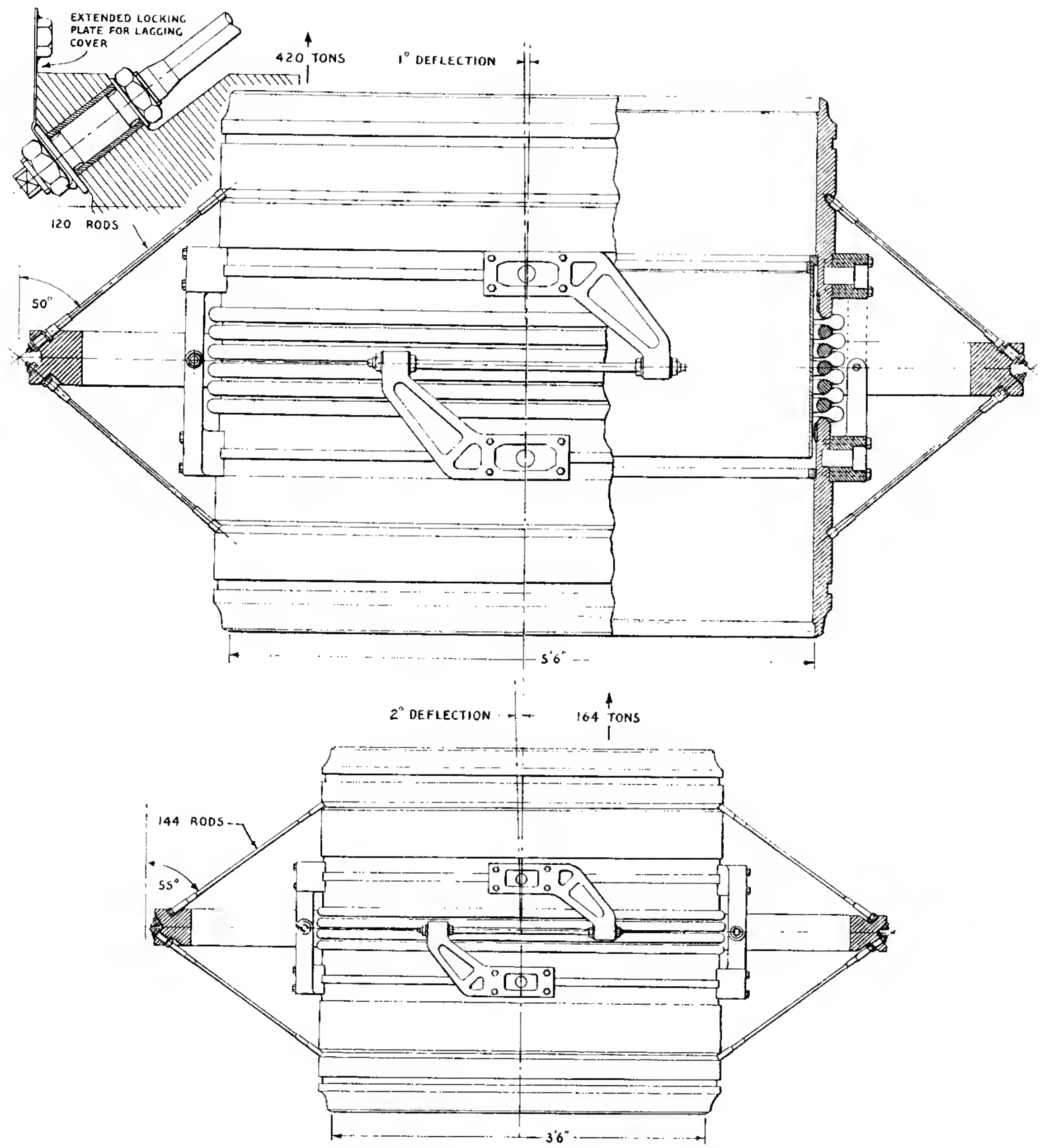

Fig. 11. Comparison of frusto-conical restraint units for main and recirculating gas ducts. Notice different cone angles, number, length and diameter of rods for different end loads and angles of deflection.

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DESIGN AND DEVELOPMENT BELLOWS RESTRAINT UNIT (E)

Further Background

DESIGN AND DEVELOPMENT
BELLOWS RESTRAINT UNIT (E)

Further Background

The historical background recorded previously was purposely restricted so as to approximate to the knowledge available to R.W.G. designers. In fact, of course, a great deal of work had been done in other Companies developing restraint units in parallel with the earlier flexible tongue unit, although very little information had been released at the time of the R.W.G. design.

The first three nuclear power stations started were those of Hunterston, Bradwell and Berkeley, being designed and built respectively by the G.E.C.–Simon-Carves Group, the N.P.P.C. and the A.E.I.–John Thompson Group. Shortly afterwards a fourth contract was placed with the English Electric–Babcock & Wilcox Group for the Hinkley Point station. Each design incorporated large scale gas ducting and each had a requirement for large bellows restraint units.

Large Hinge-Pin Units

At this time there was only one well-known specialist company with great experience of bellows and restraint units in large sizes—the German firm Industrie-Werke Karlsruhe—and contact was made between G.E.C. and I.W.K.'s representatives in Britain, Engineering Appliances Ltd. I.W.K. agreed to develop a hinge-pin unit to suit G.E.C.'s specification and to manufacture all the units required. The conditions for this new requirement as a whole were somewhat in excess of what I.W.K. had attempted previously, but not greatly so. A 5 ft. diameter bellows for a nominal pressure of 165 p.s.i. and for a gas temperature of up to 400°C was produced and tested. A prototype hinge-pin restraint was then designed and made for testing. This is shown in Fig. 13(C). Under pressure the rigidity afforded by the stiffening flanges was found to be quite inadequate leading to unacceptable distortion. An attempt was made to increase stiffness by welding webs between the flanges but this was only a marginal improvement. The unit was, therefore, redesigned as in (D), where stiffness was obtained by having effectively annular boxes welded on to each duct end. A long series of tests showed this arrangement to be extremely successful.

A great deal of consideration also had to be given to the pins and bearings. They would be carrying a high load for long periods at a high temperature. The full movement would only amount to, say, 3° and this might occur only at intervals of many months when a gas circuit was closed down. This was a lot to ask of bearing surfaces and a number of tests were put in hand using chromium plated, nitrided, "Stellite" coated and "Sulfinuz" treated pin surfaces, until satisfactory results were obtained.

At a later date the G.E.C. Group also won the contract for the Tokai Mura station in Japan, and I.W.K. successfully made similar restraint units for this station of 6 ft. diameter.

In the meantime, while Parsons, with their

experience of the Calder Hall units, were undertaking the complete design of restraints for Bradwell, both A.E.I. and Babcock started negotiations with I.W.K.

Babcock, who were dealing with the ductwork, pressure vessels, heat-exchangers, etc., in their entirety for the Hinkley Point station, were concerned with procuring bellows restraints. In an earlier study they had tried to overcome the use of bellows by designing ducts with inherent flexibility, accomplished by using a number of ducts 2 ft. 9 in. diameter instead of one large duct of 5 or 6 ft. diameter for each circuit. This was not entirely successful, probably on account of the power required to pump the gas round the circuit, and in the Hinkley Point ducts tied bellows were specified in each section of the ducting. Pumping power is an important item in the design of atomic power stations as it affects the overall efficiency and this has to be considered over a working life period of at least 20 years. It was reckoned that it should be possible to make suitable bellows up to between 5 ft. 6 in. and 6 ft. diameter, and negotiations were started with I.W.K. who, in due course, produced and tested a prototype bellows of 5 ft. 6 in. diameter at 250 p.s.i. pressure and at 410°C temperature.

In the meantime, ducting systems were worked out based on 5 ft. 6 in. bore and 6 ft. 6 in. bore for comparison. In addition, a further ducting layout was investigated of 6 ft. 6 in. bore but narrowing to 5 ft. 6 in. at the points where bellows were to be fitted. The latter scheme proved to be the winner on the count of cost, this being measured in terms of capital and running costs, allowing for 5 ft. 6 in. bore valves as well as bellows. Accordingly, while the nominal bore of the Hinkley Point station ducts was 6 ft. 6 in., the restraint units were made to take 5 ft. 6 in. bellows.

For the restraint units themselves, hinge-pin, external tongue and internal tongue types were considered. The tongue types were disliked for many reasons, notably that they had no fixed centre of rotation so that bellows movement, and thus bellows stress, could not be predicted accurately. Hinges could, of course, be added, but it seemed expensive to "double up" when one might just as well use hinges as the kinematic constraint and for load carrying. A lot of consideration had to be given to the idea of using a hinge pin design. The nearest known precedent (apart from the type used at Calder Hall, which was considered expensive) was below 3 ft. in diameter with a pressure of about 200 p.s.i. Stiffening the duct flanges adequately to transfer the end load from the duct walls to the hinge plates seemed feasible and by choosing the right pin size bearing pressures need not be excessively high. It was, however, recognised that the choice of bearing and pin materials would be important and that under the specific conditions—very small and infrequent movement, high temperature and high load—there might be a variation, probably adverse, of the turning moment over time. Feasibility, therefore, depended upon an assessment of the likely turning moment under the worst expected conditions. Using assumptions based on experience, calculations suggested that under the most adverse conditions the turning moment should not increase to the point of being dangerous and it was agreed, therefore, to design a hinge pin restraint along the most simple lines possible. Not least, it was possible to estimate the probable cost of these units fairly closely, whereas the development work which might be necessary to produce

a suitable tongue design made costing difficult. These studies were carried out because it had been decided by Babcock that they should produce their own restraint units with a specialist firm providing the convoluted bellows.

I.W.K. had by this time built their second prototype unit for the G.E.C. contract (Fig. 13(D)) and a similar unit was constructed to test the 5 ft. 6 in. prototype bellows required by Babcock. Some of Babcock's engineers were present at this test and there is little doubt that the sight of this unit adequately taking the transfer of load from the hinge pin arms without distortion confirmed Babcock's decision to design a hinge pin unit. The close relations built up between I.W.K. and Babcock engineers during this development period led to the latter Company acquiring a fair amount of information with respect to hinge pin units from the German Company. This was not really unreasonable commercial practice. Each of the early nuclear power stations required about 100 large bellows restraint units apiece; I.W.K. were already providing those for two G.E.C. stations, and were also making the convoluted bellows for two other stations—Berkeley and Hinkley Point. Naturally, I.W.K. had a limited capacity and they could hardly expect to provide, and therefore aim to provide, all the complete restraint units for the stations being built in parallel. Some of the nuclear power stations would have to have British made units and the provision of some technical advice to firms buying I.W.K. bellows made for better relations.

Apart from this transfer of information, both the Babcock and the German restraints were extrapolations of orthodox practice and were necessarily similar. Stiffness was obtained by making the duct ends considerably thicker than the duct walls and by building large stiffening rings around each end, these being of hollow box type construction with radial webs. Particular attention was paid to the choice of materials, sizes and clearances of the hinge pins, bearing bushes and so on. Apart from the usual minor modifications which are natural in work of this scale, no serious difficulties were encountered; tests were completed satisfactorily and production units were put in hand within a year of starting the project.

The pins were lubricated with molybdenum disulphide. As this substance had not been in use for 20 years, nipples were provided so that lubricant could be renewed if necessary. The pins were also given square heads so that their freedom of movement could be checked when the units were unloaded.

When the Sizewell project came to hand, another complete reassessment was made, and on cost grounds it was agreed to retain 5 ft. 6 in. bellows with the ducting again of 6 ft. 6 in. diameter. The gas circulators were made integral with the heat exchangers, so that the three sections in each duct at Hinkley Point were reduced to two sections at Sizewell—a hot and cold leg—with only 6 tied bellows per circuit instead of 9. At a number of points mitred bends were replaced with smooth radiused bends and, when calculations were made for the upper hot duct leg, it became apparent that bellows would not be required as these ducts would have sufficient inherent flexibility; the number of restraints required per circuit was, therefore, reduced to 3 on the cold leg.

The design of the hinge pin restraint units

for the Sizewell circuits followed very closely that of the Hinkley Point models, minor changes being made, including choice of materials, to take the higher gas pressure and temperature.

In the meantime, the contract for the bellows in the Hinkley Point recirculating ducts–considerably smaller than the main duct bellows–had been given to a British Company, Teddington Aircraft Controls (Bellows Division) Ltd. Though originally interested in small bellows for instrument work, T.A.C. were embarking upon larger scale work with the encouragement from Babcock & Wilcox they eventually developed their own bellows of a size suitable for nuclear power station ducting. Consequently, when R.W.G. embarked upon their restraint design in 1959 a suitable bellows could be obtained from a British Company. Figure 13(A) shows a prototype bellows for the Trawsfynydd station being tested by Teddington Aircraft Controls Ltd., Bellows Division, in a hinge pin test rig designed in conjunction with Messrs. Babcock & Wilcox Ltd.

Tie-Bar Unit

Parallel with these events, negotiations had been going on between A.E.I. and I.W.K. with reference to restraint units for Berkeley. After an appraisal of the duct operating conditions, A.E.I. engineers expressed grave doubts over the use of hinge-pin units, particularly over their long term characteristics in respect of this specific use. They accordingly decided only to procure convoluted bellows from I.W.K., designing their own restraint unit on flexing principles. These views were recorded in 1959:

"It was thought that hinge pin constraints would not be able to cater for such high loads, particularly as the hinge for the bellows in service would be at temperature and would probably not move for months at a time. Such conditions would be ideal for squeezing out any lubricant that might remain on the pin and also ideal for causing galling and seizure of the bearing surface.

"If under such conditions, galling or seizure occurred the resulting excessive torque to cause deflection of the bellows would probably dangerously overstress the pressure vessel at the weakest point–the duct branches. A disturbing feature of this is that galling of the pin surfaces would be unknown to the station operating staff.

"The large gas pressure loading is, in the A.E.I. design of bellows, taken by two tie bars anchored at each end of the duct and inside the bellows unit. Deflection of the bellows causes flexure of the tie bars which are suitably shaped so that the bending does not incur excessive stresses.

"The use of tie bars themselves, although a satisfactory solution of the gas loading problem, was not thought to solve completely all the problems associated with their use. For example, any dead weight, thermal, wind or erection loads at one side of the bellows, not completely balanced out by hangers or other suitable means, would have to be transmitted across the convolutions by either the convolutions themselves or the tie bars. By the very nature of the design of the tie bars these would not transmit very much of this loading. This means that the weakest part of the bellows unit would be carrying additional "shear" loads for which it was not intended and because of this an early failure of the convolutions at site could easily occur–a failure due to forces which

would not normally be applied during testing in a rig.

"To transmit any such vertical out-of-balance forces which might be encountered at site, the Berkeley bellows units are made with brackets and hingepins—the hinges being so designed that they do not take any axial (gas pressure) loads. In addition there are interlocking key brackets at each side of the bellows and at right angles to the hinges to transmit any side loads from one flange of the bellows to the other, so that the convolutions themselves are clear of this type of extraneous loading. Furthermore, both the key brackets and hinges take care of any extraneous torsional loading that might be applied to the unit.... The hinges are sufficiently strong to act as a safety device should the internal restraints fail."

After mentioning some of the tests carried out, this quotation continued:

"To simulate conditions in service a prototype bellows should be subjected not only to deflection but also (at the same time) to cycles of pressure and temperature. If closer simulation is required it should also be subjected to conditions of corrosion and stress relaxation due to creep. Tests on prototype bellows have not, therefore, up to now simulated all conditions that occur in service."

From the Patent Specification and a later article we may assume that the original intention, if at all possible, was to keep the bore free by placing the tie bars externally, as in the experimental unit Fig. 14(A). The distortion of the duct flanges, however, proved to be greater than was compatible with long life for the bellows—at least in the higher pressure ranges—and in all subsequent models, experimental and production, the tie bars were mounted internally which gave a more rigid anchorage. (Figs. 14(B), (C) & (D)).

Having proved this restraint in test rigs and embarked upon fulfilling the order for Berkeley, A.E.I. began to look ahead to future requirements. It would be useful, for instance, if duct diameters could be increased and, even if they were not, pressure would undoubtedly rise and the problem would move away from the restraint itself to the flexible element again. In any case, the Company presumably and quite naturally disliked having to rely on a foreign Company for bellows, and the development of bellows for yet higher duty would be expensive.

Attention was, therefore, turned to the possibility of designing a new kind of flexible element which could be manufactured by the Company without the use of special tools and equipment. The design which was finally evolved consisted of diaphragms suitably backed by special plates (Fig. 14(E)). Prototype fabricated flexible elements were tested satisfactorily and were later substituted for the convoluted bellows in some of the experimental restraints for further testing, the results being very successful. Figure 14(D) illustrates an experimental design using these fabricated flexible elements.

Subsequent Changes

When the Advanced Gas Cooled Reactor was being designed by the U.K.A.E.A. in 1958 it proved to be impossible to extrapolate the Calder Hall design insofar as the ducting was concerned. The changes are

recorded briefly by Dr. G. Brown in the Discussion following the Bowden and Drumm Paper:

"On the Advanced Gas Cooled Reactor (A.G.R.) in which the design temperatures were 325°C for inlet and 575°C for outlet the expansion problems were aggravated. It would be observed that there was a great change from Calder Hall; the inlet temperature on A.G.R. was almost identical with the top temperature at Calder Hall. The various duct types described in the paper had been considered, but even with relatively small ducts 2 ft. in diameter they were not satisfied with the layouts obtained. (The layout of the A.G.R. ducts is shown in Fig. 15)... It would be observed that the reactor support was on the same level as the ducts. The short ducts between heat exchanger and reactor gave compactness in design. The heat exchanger was on ball-bearing support and moved radially with expansion. In the concentric duct arrangement the hot outlet gas flowed in the inner duct with the cool inlet gas in contraflow in the annulus. Both ducts operated at inlet gas temperature since the inner duct was insulated internally. Differential expansion between the two ducts was taken by compression bellows at the heat exchanger end of the inner duct..."

At the time of writing, two new nuclear power stations are in the design stage—Oldbury, by the Nuclear Power Group, and Wylfa, probably to be shared between the United Power Company and the English Electric Group. Both will probably use pre-stressed concrete pressure vessels instead of steel ones and completely new problems will have to be met. No information is available concerning the form of these new designs, but the following is extracted from the leader of "Nuclear Engineering," April, 1962, concerning the Oldbury plant:

"...With limited time at their disposal and fearful of making too big a jump, T.N.P.G. have in effect put a Dungeness core inside a concrete vessel, including at the same time, in an annulus around the core, banks of heat exchanger tubing. These banks are shielded from the core by a steel and graphite wall which should allow entry for maintenance with the reactor shut down..."

Short as this quotation is, it suggests that the layouts for the new generations of gas-cooled graphite-moderated reactors will not raise the problems of ducts and expansion joints discussed in this paper. After 10 years it is clear that this is the case. Developments in nuclear power station design in Britain effectively did away with a requirement for ducting of the kind discussed and, like dinosaurs, these rather massive restraint designs have come to a dead end, although they could be revived in years to come in general plant work. So far no trouble has been reported from any of these units in service.

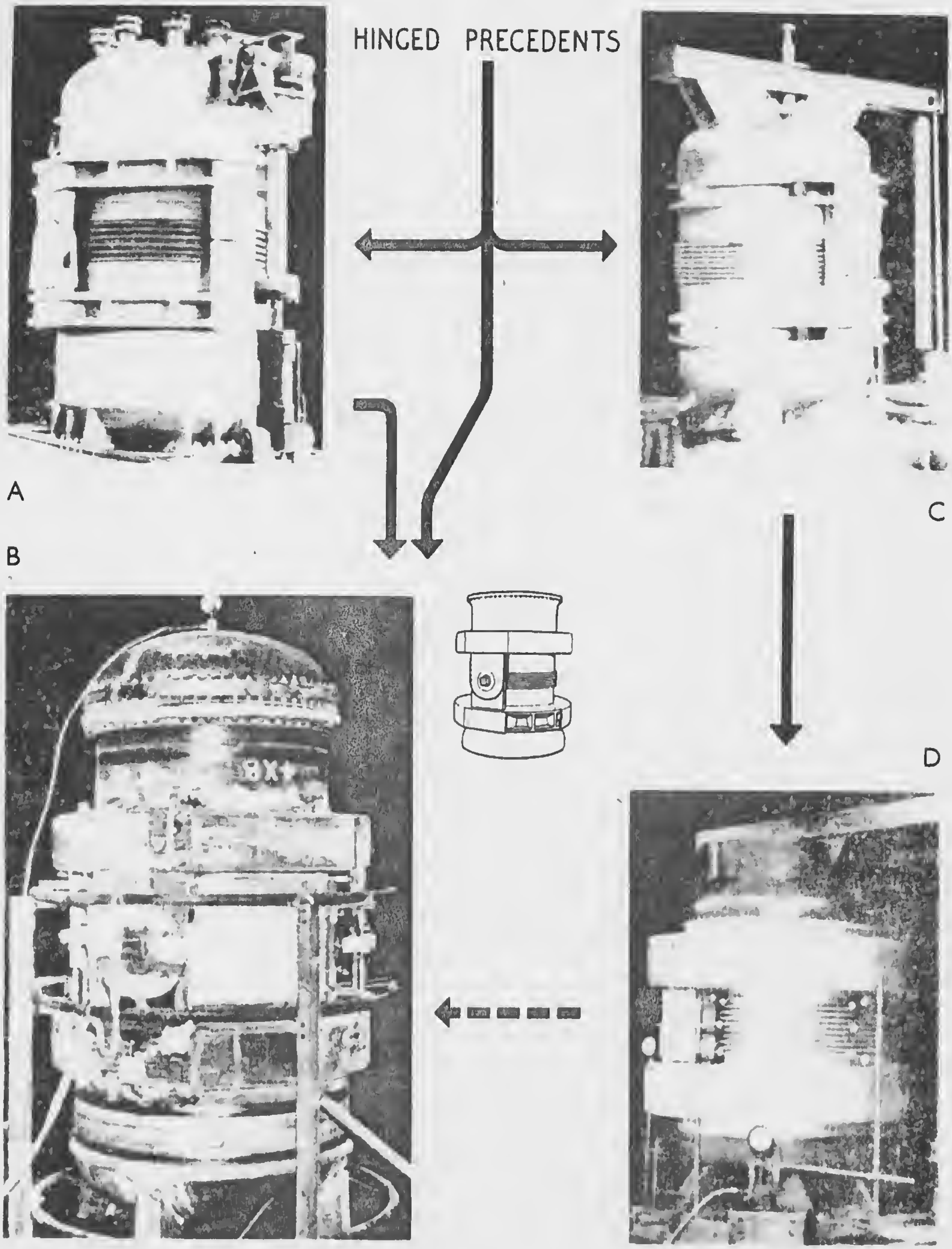


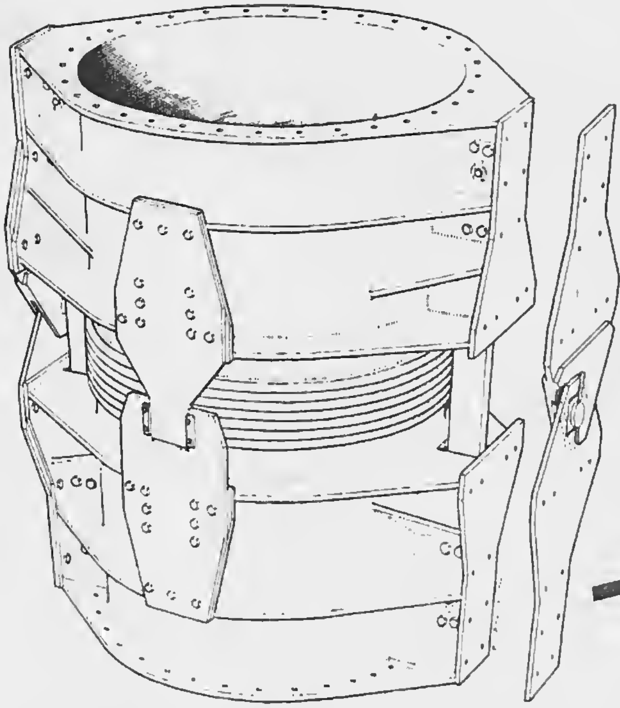
Fig. 13.

A A restraint unit used by Teddington Aircraft Controls Ltd., Bellows Division, to test their 66in. diameter bellows: designed in conjunction with Messrs. Babcock & Wilcox Ltd.

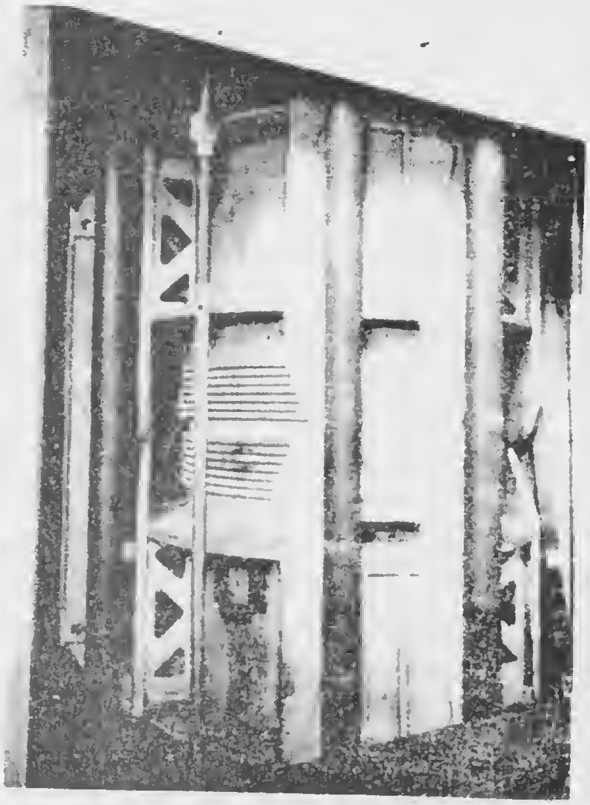
B The prototype Babcock & Wilcox restraint unit under test. The unit is here being tested mainly for structural stiffness; the bellows is not that used in the production models. Notice (see inset) that whilst stiffening boxes have wrap-round plates, the construction below is similar to that of A. The production units vary in appearance according to their positions in the circuit.

C The experimental 5 ft. restraint made by I.W.K. Deflection of the flanges proved to be excessive and the unit was redesigned as in D.

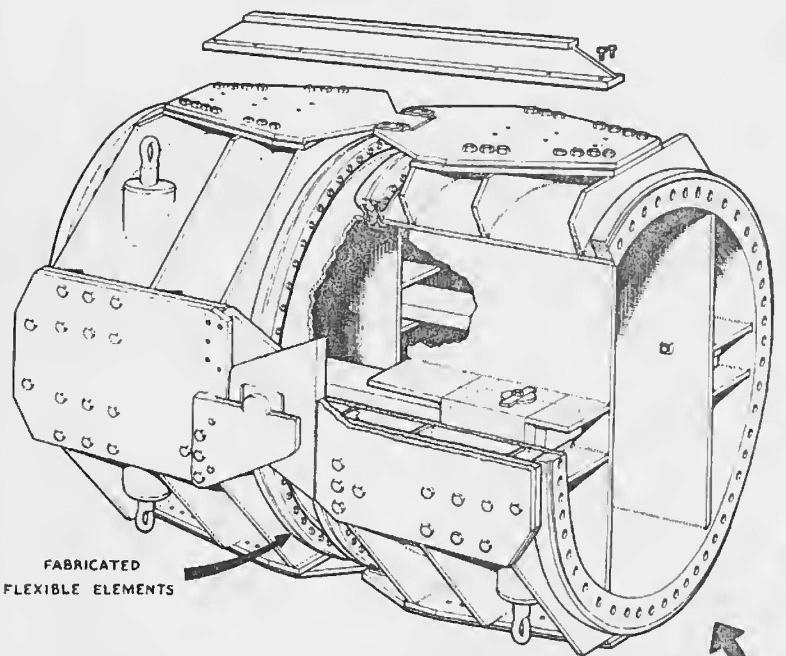
D Prototype restraint built by I.W.K. Stiffening boxes are hollow and the production units for Hunterston were nearly identical.



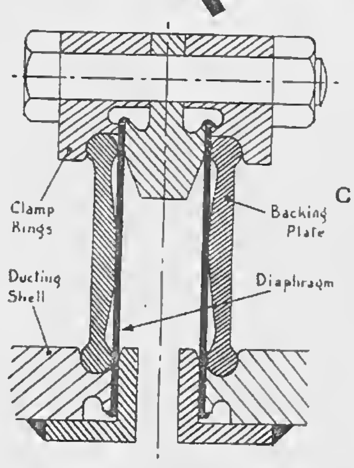
A Experimental restraint with external tie bars, floating hinges and key brackets.



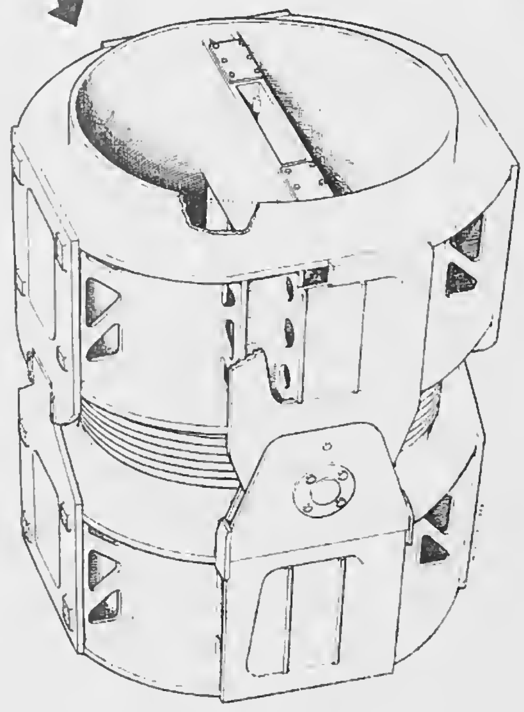
B Prototype restraint unit for Berkeley in test rig.



D A later experimental restraint using fabricated flexible elements instead of conventional bellows.



E Simplified section through fabricated flexible elements.



C Production units for Berkeley. Whereas the experimental units were of bolted construction to facilitate changes, production units were largely welded and this, together with Internal tie bar produced a more compact and pleasing unit (su sequently lagged).

Fig. 14.

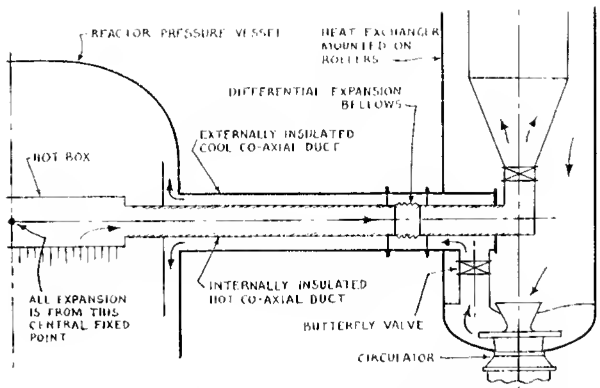


Fig. 15. Duct layout for Advanced Gas-Cooled Reactor.

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DESIGN AND DEVELOPMENT BELLOWS RESTRAINT UNIT (F)

Principles and Precedents in Engineering Design

DESIGN AND DEVELOPMENT BELLOWS RESTRAINT UNIT (F)

Principles and Precedents in Engineering Design

The story given in the preceding parts is sufficiently extensive to be of interest in itself and to be analysed in many quite different directions. The observations which follow are restricted to certain lines which tend to supplement rather than duplicate what has been written elsewhere.

Design Continuity

Probably the most striking feature of this design story is the essential continuity, in which everything is a function of what preceded it. A nuclear power station may be new in that it uses an unorthodox heat source, but its design as a whole is based on a long line of thermal power stations. The gas ducts may be working under extended conditions but their design stems directly from gas-turbine, steam-turbine and chemical plant practice. We may, indeed, say that no design starts entirely from scratch and that, in engineering, no design is entirely a simple synthesis of generalised knowledge.

There are, of course, reasons for this but let us first view this continuity through a generalised picture of design.

Generalised Model of Engineering Design

Analysis of the design of any of the recorded design entities—be it a nuclear power station, a gas circuit, a bellows restraint unit, a tie-rod or a hinge pin—shows a pattern which accords to a greater or lesser degree with that shown in Fig. 16. At the top is the Specification of the requirement, which is generally more applicable than the term Problem. This Specification is based upon a knowledge of what is in existence and is generally an extrapolation of an already satisfied requirement.

The Designer receiving this Specification has to arrive at an arrangement of other designs, of sub-assemblies or parts as the case may be, which will satisfy this requirement. Since the requirement may well be something complex, where possible he will turn to the nearest precedent—sometimes the same thing which inspired the Specification. This precedent may be something this Designer or his group has worked upon, or it may be the design of a competitor. The precedent, viewed in a generalised way, will be examined with respect to the Specification. It will not exactly fit the requirement—if it did there would be no cause for design. (This is only true as a first approximation. Commercial and political considerations sometimes lead to duplicating design.) The Designer will therefore postulate successive modifications with a view to bringing the initial ideas for an arrangement in line with the Specification, these modifications being both quantitative and qualitative as may be necessary, including optimisation of parameters and a filling out of the arrangement to give a scaled layout. Eventually, an arrangement may emerge for evaluation.

If this is clearly the best line to follow, the Designer may then proceed directly to the

succeeding stages. However, it might not be possible or desirable to use this kind of arrangement in some new circumstances embodied in the Specification, or because of Patent infringements, etc. He will then have to look elsewhere, suggesting further basic arrangements, each of which is derived from some more remote precedent or one from another field of engineering. Each will be successively modified as for Arrangement. (1)

If a number of arrangements do reach a certain stage, i.e., more than one is judged feasible, they will be evaluated in comparison, not only in respect to the Specification but also with respect to estimations of how much additional effort will be required (i.e., Development). If a choice arises, one of the arrangements will be selected, although it may go through further modification stages before reaching the Breakdown. Here the arrangement is broken down into its constituent parts, sub-assemblies and so on, each of which is a design entity in itself. Each has a specification, real or implied, whether in a formal form or not, and for each of these the whole of this diagram may be considered to follow on a reduced scale, including all that existing below the Breakdown.

Each of these Sub-Assemblies or Parts may develop in a manner similar to that applicable to the Arrangement considered at the top of the diagram—with possibly more than one basic form to choose from and development through successive modification—except that in the case of Parts, "Shape and Material" will take the place of the word "Arrangement." Some of the Specifications may be put out to other firms at some stage, and sometimes a ready-made or ready-designed item may be available—which simply means that this general design pattern has already been followed through for these particular items.

Eventually a number of drawings, lists, specifications, etc., will have been produced which, in total, represent The Design insofar as definition is concerned. There will be a General Arrangement drawing, based on the selected arrangement but modified to take account of the final form of Sub-Assemblies and Parts arrived at; and there will be Sub-Assembly and Part drawings, each based upon the original postulated arrangement or shape but modified to take account of the stages occurring under the heading "Breakdown."

All the various parts will then be made or procured and assembled for testing. Apart from formal testing, the operational service of the equipment is also a form of test, and from any time hereon shortcomings and faults will probably be found.

The resulting design—whether it be a scale model, a prototype or a production version—will provide from its performance information from which a further specification can emerge, and in itself it will serve as a precedent for the next design of its kind. In other words, the whole of this diagram may be repeated at both top and bottom to give, in effect, a continuous process stretching out indefinitely in both directions.

The Design will also be a precedent for other Designers possibly working in other fields, so that Fig. 16 may be connected to many other such diagrams in each one of which this design enters as at the top in the form "Remote Precedent or One from Another Field."

One has, then, a basic diagram representing one cycle of a process. This process is, however, repeated within itself a number of times and perhaps within itself again at different levels. The process also repeats itself continuously end onwards, not only for the main design, but for all the sub-design entities. To make the picture more complicated still, this endless series of cycles at many levels is repeated in parallel any number of times representing other designs, so that any scheme, arrangement or shape at any level may become a precedent for any similar situation in any other parallel stream.

Evaluation and Breakdown

The point of Evaluation coincides with the "critical decision" thesis dealt with by Marples. Whilst it is convenient in a diagram to place "Evaluation" in the position shown in Fig. 16, there need, in fact, be no clear point where a decision is made. Arrangements will accumulate for a formal comparative evaluation in certain situations, i.e., when the solutions provided come from different sources (e.g. tenders from other firms), when the solutions are ready-made or ready-designed items, when the solutions in principle are readily apparent, or when none of the solutions is obviously more advantageous. Solutions in this context, of course, refers to what appear to be solutions at the time of postulation. Some will eventually prove to be unfeasible, in which case they are not solutions.

On the other hand, we must recognise that any line of solution will be evaluated to a greater or lesser extent so soon as it is formulated. For instance, in Fig. 6, the hinge pin solution was regarded as feasible but it was rated as commercially unfavourable. Being feasible it was not eliminated, but the unfavourable evaluation was the motivation for a further search for solutions. Only one solution—the single tongue—was judged unfeasible, though only the frusto-conical idea had a favourable evaluation. This being so, a formal comparison between all feasible solutions was probably unnecessary.

Notice that whilst solutions (1) and (2) could be postulated in principle at the start, being from direct precedents, the other solutions were different in character; they required a great deal of hard thinking and, being relatively new, were more speculative.

Consequently, whilst known solutions in principle may be postulated at the start, solutions formulated within one group or by one person tend to follow one another. Each requires time and much mental effort, and the motivation for expending these is an unfeasible technical assessment or an unfavourable commercial evaluation of previous solutions. This is considered further in a later section.

The Breakdown which follows Evaluation also need not imply a distinct point in time at which something happens. Previous to Evaluation the various sub-assemblies and parts will have been investigated to a greater or lesser degree, because the feasibility of the major design entity will depend upon the assessed practicability of these minor design entities. After Breakdown the investigation, as it were, becomes more detailed but continues to give a more and more exact definition to the parts and to the whole. In a major layout Breakdown can be seen formally in the drawing up of

written specifications. In smaller layouts Breakdown is simply a convenient way of saying that the Designer gives increasing attention to the more minor design entities.

In a major layout specifications arise of a formal nature and are recognised as such. However, "specifications" exist in effect throughout engineering design at all levels; they may take the form of words, figures, drawings or sketches, and are quite often simply implied by the arrangement confronting the Designer. In general they may be defined as a description of what is required *insofar as it is known at that time.*

Quite obviously, then, as the design progresses there are bound to be changes of various kinds in the specifications, depending upon how well the situation was assessed in the first place. For instance, at the start of the R.W.G. design a figure for maximum bending moment was given; no figure for shear load was given though a small load of this kind was assumed. In the event, as the duct design advanced, the maximum bending moment figure was reduced and the minimum shear load figure was increased. Alterations like this, depending upon the circumstances, might entail anything from no change to a major design change (See e.g. Ref. 5). This is inherent in design and it is the continual changes of a minor or major character moving upwards and downwards which tend to make design appear chaotic to the observer.

Development

In a generalised way, development may be regarded as the repetition of the Design Cycle depicted in Fig. 16 until a satisfactory design emerges. The first cycle might be concerned with the design, making and testing of a scale model, the results of which affect the second cycle from which a prototype emerges, and successive cycles end up, perhaps, with a series of production designs. The design as a whole might not, of course, need such development, the latter applying to a contained Sub-Assembly or Part—but as the diagram representing the process applicable to the Part is essentially the same as that applying to the whole, this is just a matter of "changing the scale" to suit the appropriate level.

Development may be concerned with a number of design cycles only the last of which leads to a commercial product. On the other hand the term development can equally be applied to a series of long term overall design cycles each of which produces a marketable product.

Going in the other direction, all the drawing board work in one cycle may itself be called development since it is a question of making successive improvements on paper before hardware is manufactured.

Sometimes an unusual problem turns up in engineering which is not defined clearly enough for a proper Specification to be issued. This quite often happens in special purposes machinery design where something may have to be done which has not—at least to the Designer's knowledge—a sufficiently close precedent. In such cases the Designer will often go through the first cycle as quickly as possible—postulating something, constructing it from available parts and testing it. From this he can then assess more clearly the requirements and the shortcomings of the postulated arrangement. After one, two or more such cycles, sufficient data will be at hand to draw up a more formal Specification, whilst the hardware mock-ups tested will become the

precedents to build upon. The design may then proceed formally through the stages of Fig. 16. The case in Ref. (6) is a good one of this type.

An interesting feature of this excursion is that, with sufficient knowledge of comparable precedents, instead of the Designer rushing through to hardware in order to make tests, he will be able to go through these cycles in his own imagination, each time modifying his arrangement to suite what he estimates to be its shortcomings. In other words, we may postulate that the words "Modify" which occur in Fig. 16 sometimes represent more or less the whole of this generalised design process carried out in the imagination.

To what extent this can in fact be done reliably is the theme of subsequent sections.

Precedents in Engineering Design

Considered at a very high level of abstraction, there is much common in all design work whether it be typographical layout or industrial design in the appearance sense. Engineering design, however, differs in a number of important respects when viewed at a more realistic level. Firstly, very little engineering is on such a scale that one man can deal personally with a design from beginning to end. Successive breakdowns and successive specifications create an organisational picture which can become very complex, in that one is using a number of individual minds to work creatively within one project. Secondly, as we have seen, engineering design is essentially a continuous process in which precedents of one kind or another play a predominant part.

There are two main reasons why engineering design takes this cyclic form. They are firstly, the properties of material things and the way we can recognise and deal with them, and secondly the commercial nature of engineering.

Properties of Materials and Arrangements

In devising an arrangement to satisfy a specification one has to postulate an arrangement which has a number of properties. The only way we can do this at all is to base our arrangement upon some known precedent—close, if possible, remote, if necessary.

All material objects and all arrangements of material parts have properties, which are considerable in number, if not limitless. In estimating behaviour appropriate to the particular circumstances of an engineering situation, the Designer has to be able to recognise relevant properties and assess their significance. Without comparable precedents this cannot be done with any completeness or certainty. If the Designer is familiar with a close precedent, then he can isolate with fair confidence the relevant properties because he knows of the precedent's behaviour. As the precedent used becomes more and more remote from the actual circumstances, so the confidence that the Designer has in prediction falls, not only on the score of quantitative assessment, but even on a recognition of relevant properties.

Any arrangement, scheme or shape postulated to give certain properties will always have a number of other incidental properties, many of which will be relevant to the new situation. They may be considered disadvantageous in which case modifica-

tions will be postulated to eliminate them or reduce their significance; they may, on the other hand, be advantageous in the circumstances, giving a "bonus" over and above what was aimed for, and this can often be exploited.

The Tie-Bar Restraint gives us a simple example of successively overcoming disadvantageous properties. The idea of using hinges for taking the load was dropped in favour of flexing tie-bars, whose bending moment would be constant and predictable. This arrangement suffered from having no fixed centre or rotation, and this was overcome by giving it one in the shape of light hinge plates with a floating bearing. This, however, had little lateral or torsional stiffness and this was overcome by adding key-brackets. This successive modification to overcome shortcomings of previous modifications can be taken too far by inexperienced designers with what is often called a "clumsy" result.

The Frusto-Conical Restraint provides a good example of a "bonus." The rods were placed uniformly round the unit to spread evenly the transfer of load, i.e., to minimise stress concentrations. This hardly called for thought, since the rods were a replacement for the solid surface of the precedent, the turbine bearing housing. This arrangement, however, resulted in a universal joint which, though not a requirement of the specification, was nevertheless an advantage. Bonuses like this are not planned into the design; they arise, being incidental properties of arrangements proposed for other reasons, but recognised and exploited they can become selling points. Notice that, although universality was not a specified requirement, R.W.G. engineers turned down anti-shear proposals, such as light hinges, which would have destroyed this advantageous incidental property.

Properties, Principles and Calculations

The properties of any given arrangements, schemes or shapes of material objects are not only not self-evident in any given circumstances; quite often they are of a comparative nature only. All material bodies, for example, have some rigidity; conversely they all have some flexibility. Whether an element, therefore, is considered to be sensibly rigid or flexible will rest on its comparison with other interacting elements. To judge such things the Designer needs numerical data and very often this is calculated information. Examples would be those calculations which led Parsons' engineers not to add hinges to the flexible tongue restraint, and those which led R.W.G. engineers to substitute anti-shear units for dog-teeth.

We must remember, however, that mathematical models and the like are man-made abstractions. They deal with certain selected parameters and properties which appear to be common to general situations of a type, and they relate these according to rules which engineers and scientists have given them. The basis for accepting these abstractions is that they give tolerably accurate results within the limits of known experience. Extrapolating these abstractions beyond the limits of experimental or operational evidence is little more than an act of faith. Sometimes the results obtained are still reasonably accurate—sometimes they are a long way out, often because some property, not taken into account in arriving at the mathematical model, assumes significance, though one can only know in retrospect.

An interesting example of replacing a complex situation by an "equivalent" abstraction is the substitution of an "equivalent" cylindrical bearing housing for the frusto-conical one referred to in connection with Fig. 6 and the prediction of the shortening, and hence bending moment, of the prototype frusto-conical restraint is similar. In every case the observed effects were explainable in retrospect in terms of other principles and when thus understood by the Designer confidence returned.

We may also note that both the original experimental restraints made by I.W.K. and A.E.I. showed that flange stiffness had been underestimated, although extensive calculations–based on results in smaller units–had been carried out. Also that it was this fear of extrapolating unreasonably beyond hardware evidence which led to inherently flexible ducting being turned down for kinematic ducting in the first nuclear power stations; the same fear too led to the rejection in some quarters of hinge-pins restraints for flexible elements.

We may say that the application of theories or principles is a function of how appropriate to particular real situations the Designer considers them to be. From which it follows that the Designer must have an intimate knowledge of real situations. When he has not–and realises it–he obtains hardware in one form or another and observes its behaviour. From the above we may deduce that engineering design is not a theoretical subject, but rather the use of theory to interpret, i.e., make meaningful, the properties and behaviour of the physical world with a view to varying them intelligently–and this demands that the Designer should always be close to material things, in their manufacture, construction and testing, for whatever devices or manoeuvres he uses on the way he must eventually get back to reality.

Consequently, the increasing use of calculations in engineering does not fundamentally change the thesis of the previous sections, since the interpretation of figures and their validity or significance depends upon the Designers' recognition of what the relevant properties of the reality are likely to be, based upon his experience of similar hardware behaviour.

The engineering designer is in any case concerned with so many properties, such as reliability, safety, maintainability, etc., as well as the more tangible ones–properties which are only truly assessible from operating experience. Hence the natural tendency to extrapolate as far as possible from proven precedents, and to overthrow old lines of development for new ones only when this becomes necessary.

A new approach, by definition, can have no operational experience, and no amount of theoretical estimation can be a substitute for this. The sub-problems arising cannot be foreseen in a situation outside experience. Extrapolations may allow of intelligent guesses, but these can only be substantiated by models, prototypes and tests–and even then not always, as long-term effects may not become apparent until the requisite time has passed. In any case tests are selective and limited largely to those attributes the engineer decides to test.

So long as engineering design is expected to take the form of planning on paper with a reasonable expectancy that the defined end product will do the job required of it at a

reasonably predictable price, design must be conservative to a greater or lesser degree taking the form of steady improvement over successive cycles, as implied by Fig. 16.

We see then, that with any design, whether this is amenable to numerical assessment or not, and the more so as this differs from precedent, the Designer's lot can be described as one endless struggle to try to elucidate what is relevant and/or significant in the specific circumstances.

Source of Solutions

Given a specification to fulfill, the Designer's source of solutions is now fairly clear, and can be seen in particular by reference to Fig. 6. The first postulated solution is that of the immediate precedent—if there is one. This will be examined with reference to the new conditions, which may differ in kind or degree from previous conditions. If this solution appears to be unfeasible, or feasible only if a vast amount of effort is put into it, another precedent will be taken and/or the first will be modified if possible. Sometimes a "modification" can be of such an order that the new arrangement is virtually a separate solution in its own right. The torsion bar and double-tongue solutions are treated thus in Fig. 6 though they were derived through previous solutions. This process can be repeated any number of times, the further postulated solutions arising from more and more remote precedents and/or successive modifications to earlier solutions. Aligning the whole problem and the solution becomes more and more difficult as one seeks more and more remote precedents, for this means successive simplification or abstraction—in the limit ending up with the search for a single principle—and using the brain as a sort of card index system, assuming that over a period of time it has analysed and stored many precedents and principles.

Sometimes such a mental search fails, but the analysis which led to the reduction of the problem to its simplest terms alerts one so that some quite everyday happening—which would be otherwise ignored—becomes significant and provides a basic answer.

Ignoring other factors, it is apparent that the more remote the chosen precedent is from the actual circumstances, the more effort will be needed to evolve it into a reliable, safe, economic piece of equipment. This is considered, weighed against other factors, in a later section.

It will be noticed that so-called "creativity" is a relative thing. All designs are ultimately creative in that no two are exactly alike, though the greatest creative effort may occur at varying levels. The frusto-conical restraint was undoubtedly a creative solution in the fullest sense. The elbow bends in the Trawsfynydd ducting (see Fig. 5)—which incidentally were conceived by the same design team and are based on the principle that a sphere is the strongest shaped vessel for a given thickness of plate—also rank as creative solutions. However, the major design entity, the duct circuit itself, is relatively unchanged from precedent. Going the other way, whilst the frusto-conical arrangement as a whole was unaffected, the substitution of the anti-shear units for dog-teeth was decidedly creative at its own level.

Independent Invention

Nobody, of course, has a monopoly over

inventiveness. Because design as a whole advances from one model to another, it does not follow that two similar solutions are necessarily directly connected. Independent invention is apparent throughout recorded history. There is, in fact, an example of such independent invention within the context of this recorded story.

The frusto-conical restraint was derived from a particular precedent–distortion in a bearing housing–imprinted on one or more persons' minds because of the initial circumstances. Naturally, the frusto-conical principle was not unique to this event. It was used many years ago as shown in Fig. 17 simply to join two pipe ends flexibly. This idea has often, incidentally, been exploited by welding a number of such fabricated frusto-cones together to form a bellows. Readers may themselves be aware of other examples.

The frusto-conical idea not being completely unique, it is not surprising to find that someone else thought of applying it to the general duct joint problem. A German patent in the name of the Swiss firm Brown, Boverie et Cie, shows the same fundamental idea developed rather differently. Figure 18 is based upon the drawings appearing in the patent.

Viewed at the highest level of abstraction these and the R.W.G. units are alike in that both exploit a basic principle. As we come down, however, we see that they were divergent in development. In Fig. 18(A) the conical lattice is made up of a number of individual wires, the ends of each being anchored to the duct on either side of the flexible joint, while their centres ride in slots cut in the annular ring. Under tension the wires are straight, the slight bending due to joint rotation taking place where the wires are anchored or supported. In (B) a heavier continual wire hawser is used with half-sheaves at anchor points. In (C) a much more robust unit emerges where the links are made strong enough to take compression as well as tension. Movement is accommodated through spherical seatings at the ends of links, which are adjustable in length.

The Brown, Boverie idea therefore–at least according to these drawings–develops into a kinematic unit, a three-dimensional version of the links in (B) and (C) of Fig. 6. The R.W.G. unit on the other hand, completely rejects mechanical movement in favour of controlled flexibility.

Needless to say, these patent drawings exhibit general ideas only and bear little resemblance to practical hardware units. Because these patent drawings exist, it does not follow that all or any of the arrangements were or could be developed into commercially acceptable pieces of equipment. Persons outside the world of engineering generally only hear of successful projects and they tend to forget that many promising ideas fail on the drawing board or in subsequent development.

Experience

We are now in a position to say something about that elusive factor in engineering design termed "experience."

Let us consider firstly the start of a design. Since design depends essentially on a knowledge of precedents–over as wide a field as possible–and this knowledge can only be accumulated over an extensive period of time, this kind of experience

must play an important part in the basic solutions which can be conceived. For example, the R.W.G. restraint was the result of exploiting an unusual phenomenon observed in testing a machine; the restraint tie rods were the result of exploiting a proprietary kind of bolt—neither of which would probably be within the experience of a student or young engineer.

Secondly, assuming an arrangement is postulated, an assessment of what its behaviour is likely to be is heavily dependent upon a knowledge of the operational behaviour of similar arrangements. This particularly applies to such things as safety, reliability, maintenance, noise, etc. Even where such properties are amenable to calculation, they have to be recognised as relevant first, while what should be calculated and how the result should be interpreted is largely a matter of judgment. This, then, is another item in "experience."

Thirdly, moving from the postulation of basic solutions and assessments which lead to successive modifications, we may turn to evaluation. This is probably the most difficult of all. One has to weigh cost again return, in effect. To get any idea of costs the Designer has to be able to estimate how much further work is likely to be entailed before a suitable design emerges. Using past experience almost exclusively as a guide he has to guess at the number of design cycles likely to be necessary—either on paper, through testing parts and/or through prototypes—by judging the degree of difference between the proposed solution and other comparable solutions whose development effort is known; he also has to assess the kind of problems the proposed solution will pose production engineers. At this stage it is quite impossible to investigate these things in detail. The solution is not sufficiently defined—and to define it thus would be to carry out the very process he is trying to pre-judge! Unless an engineer has actually been employed on a particular kind of design work he can have no idea of the amount of effort involved, the type or order of decisions to be made, the time required, procurement, contract and patent difficulties, etc. And without this knowledge he is hardly in a position to make an evaluation.

Estimating return or commercial value is just as difficult. The engineer will need to have a fair idea of what is going on in the particular field in other companies. If the equipment is of the sort which fits into larger schemes, then he should have some knowledge of trends in the major design entities, although these may be outside his own Company's work. Generalised and up-to-date knowledge of this kind cannot be acquired quickly. It is true that in some special cases it is possible to employ specialists in market research, but this cannot be spread to cover every design entity at every level. In most cases the Designer must use his impressions gained from reading, from contact with the sales force, and from discussion of relevant topics with others.

It is then, not experience as such, but limited narrow experience which is the enemy of good progressive design.

Experience and Commercial Advantage

Although in this study we have been concerned only with one narrow specialised field of work, there are very pronounced differences between the designs produced by the various Companies. At first sight it

might appear that these are a reflection of the creativity of the different design teams. A closer examination, however, does not substantiate this.

Let us consider the designs produced by Parsons, A.E.I., Babcock and I.W.K., roughly in parallel. Parsons' engineers considered restraint units with "two or four external tie bars, externally mounted flexible tongues, or rolling action by a pair of interlocking hinge pieces mounted on the axis of rotation of the bellows" as well as hinge-pin designs and the flexible tongue arrangement. No details are available of the types evaluated by A.E.I., but these included hinge-pin arrangements and external tie bars, whilst it is highly probable that consideration was also given to internal tie bars and tongue units. Babcock engineers also considered hinge-pin, internal and external tongue types. I.W.K. had experience of hinge-pin units, interlocking hinge pieces and other similar types of rolling action on restraints, and no doubt considered various flexing arrangements.

In other words, in general terms, all these design teams considered the same selection of possible solutions. The fact that they chose to follow different lines was, therefore, not really a function of their creativity, but rather the result of different assessments and evaluations, these depending upon the experience of the designers concerned, the backgrounds of the Companies and their estimations of what the future might hold in this sphere.

Broadly speaking, the designs split into two main categories; those which were kinematic and followed precedent, and those which were flexible and were, at least for their size and duty, a break with precedent.

Everyone started by considering hinge-pin units because there was most design and operational experience for this type. It is also clear that everyone had some second thoughts about this which led them to postulate alternative solutions. Some eventually accepted the hinge-pin approach while others rejected it. It is difficult, with insufficient evidence, to consider all the factors in this choice but we can make some general statements.

To begin with there was technical assessment. This was not something objective, but a function of the knowledge and experience of those making the assessment. Nobody could prove or disprove on the basis of principles whether a hinge-pin could be expected to operate satisfactorily over a long period of time in such arduous conditions without giving rise to dangerous situations.

In the end, acceptance or rejection on purely technical grounds was a reflection of the faith or otherwise these particular designers had in particular solutions, and this was largely a function of the experience of the individuals.

To put it very briefly indeed, we can say that those groups of designers whose experience of bellows in ducting was more or less confined to the field of turbines had strong doubts over the use of hinges in the specified conditions. Being responsible persons they naturally tended to find solutions in which they could have more confidence. Undoubtedly they could have produced hinge-pin designs if this had been absolutely necessary, but it would have taken a great deal of effort and testing to satisfy them that their units were safe, whilst Parsons' engineers had found out from their Calder Hall units that succes-

sively uprated designs tended to demand increasing development effort. In the circumstances it would appear to be commercially more advantageous to devote the inevitable development effort towards some new kind of unit which would have a greater potential for future exploitation.

On the other hand, experience with I.W.K. and Babcock & Wilcox was different. I.W.K. engineers, being specialists, had been in close contact with hinge-pin units over many years for many applications. They had very little doubt that a suitable hinge-pin unit could be produced, although they conducted a number of tests on hinge pins and bearings to confirm this to themselves and no doubt to allay any fears on the part of their customers, G.E.C. and the C.E.G.B., as well as the insurance authorities. Babcock engineers were also aware of precedents very much closer to the requirement than were known to others and, after a very detailed appraisal, they accepted the hinge pin solution also as being the cheaper and most straightforward approach.

The R.W.G. design was produced somewhat later when, through the Bowden & Drumm paper, it was possible to estimate something of the design effort required for various types. The ideas here were conditioned by the maximum length specified and, in the long run, the choice was essentially between the orthodox hinge-pin line and the new frusto-conical approach. Because of the relative inexperience with any units of this size, a fair amount of development work was considered inevitable whatever line was adopted; consequently the one progressed was that which seemed to have the best future possibilities.

Whilst, therefore, the various Companies all considered much the same lines of solution—with the exception of the later R.W.G. case—the choice made in each case was a function of the general experience available allied to commercial advantage. Where sufficient experience was deemed to be at hand to extrapolate a known and proven arrangement this line was taken as being the cheaper and more sure of success. Where insufficient experience was available and development expenses were inevitable in any case, a new line was chosen in preference in the hope of securing commercial advantage in the future with successive models. In other words a very important factor in selection was commercial advantage—either immediately through a cheaper design, or later through a design with greater estimated potential. Much also depended upon whether a Company was designing units for their own use or whether they wanted to sell them in competition with other suppliers.

This discussion suggests that there is no fixed point at which an arrangement reverts from being possible to impossible. Technically any arrangement approaching its useful limit can be pushed that little further if those concerned have sufficient experience. If a Company has little specialist experience, then an accepted form of design can be regarded as obsolete quicker than it would be by others, for the time and money expended in development to catch up in know-how would be uneconomic for the design's limited future.

In this particular study, it is noticeable that accelerating progress in nuclear power station design led, in a few years, to the substitution of pre-stressed concrete pressure vessels for welded plate ones, which has very likely killed the market for bel-

lows restraints of this size and rating. Unless, therefore, in later years a demand arises within other fields, the particular designs considered are likely to find no further market. Consequently, from the commercial point of view, those who managed to make a straight extrapolation of a proven precedent will have profitted most. In a similar situation in another field of design, one could equally well find those Companies investing more for the future than the present realising the greater commercial advantage in the end.

These commercial aspects and particularly the difficulty of assessing the future market in a very specialised field—which can often be killed by progress elsewhere—explain to some extent why "creative" designs are not automatically welcomed as the answer to all engineering problems. Creativity in the sense of thinking up as many diverse solutions as possible is obviously a good thing, but the evaluation and selection of solutions is another matter.

Evaluation and Creativity

Thinking up as many solutions as possible, as mentioned above, needs some qualification with respect to engineering design as a whole.

As mentioned, as soon as an arrangement is postulated to satisfy a given specification, besides being assessed technically, modified and so on, it will be evaluated to a greater or lesser degree to give some idea of its commercial worth. An unfavourable evaluation does not eliminate this solution, but it provides the motivation to search for further lines of solution.

This motivation is essential to the search for a number of solutions, especially if one considers engineering design at all levels from the overall layout to the choice of a bolt. Even the most creative persons need to devote a great deal of mental effort and time to thinking up new solutions. Consequently, however desirable in principle it may seem to be "creative" at all times, this cannot possibly become the normal approach for every design entity at every level, particularly as, at evaluation, most of the new solutions will be rejected for commercial reasons. "Creative solutions" are "squeezed out" in engineering when circumstances warrant it. To put it another way, by dealing with every design problem in the "standard" way whenever possible, a design team then has the capacity to be inventive in those special quarters where it is really needed. Any other approach would be spreading creative effort too thinly and would lead to overall inefficiency.

Thus there is a balance so that creativity and the use of standards or the following of close precedents are not incompatible. Doing the latter whenever it is deemed suitable is the only way to leave free sufficient thinking capacity to deal creatively with those cases where the standard approach is judged inadequate. The acceptance of a standard solution still, of course, implies judgment and is not automatic.

Every invention takes a considerable amount of money, time and brainpower to realise. Such investment has to be amortized if engineering companies are to stay in business. Following a continual line of development, so far as is technically and commercially possible, is efficiency rather than laziness, in that it is exploiting available know-how to advantage. It is, after all, common sense that having developed the

frusto-conical restraint unit for the 66 in. duct, R.W.G. engineers would naturally try to interpret the 42 in. duct specification (and any others) in the same terms if possible.

Nobody can afford to develop something entirely new to satisfy every specification. Full exploitation of inventiveness is as necessary as the more common idea of productivity.

Causes of Design Progress

Since we have seen that all engineering designs are essentially based upon precedent, we may well ask why design progresses as it does. There has always been a steady progress though this has accelerated in recent years.

There seem to be two major causes. The first, and more obvious, cause is scientific discovery or invention. At a high level we have, for example, nuclear fission which, amongst other things, led to the present generation of nuclear power stations. At a lower level we have, for instance, the improvement of some design entity by using in a subsequent design cycle new materials or methods of production.

The second, and less obvious cause, arises out of the complexity of modern major projects and it amounts to misjudgment leading to forced invention. Because design is a continuous process, a specification is drawn up on the basis of previous designs. These, however, will have been viewed initially in very general terms and, according to how easy or difficult the previous results were obtained in the judgment of the specifier, so the sights will be raised. However, during the progress of the design it may often turn out upon closer examination that something is not attainable at some level or another. This will force a change either at that level or at some level above it. Since it becomes increasingly difficult and costly to go back and change a decision at a higher level, great creative effort will be applied to solving the problem at the lowest level–resulting in forced invention.

For example, hinge-pin bellows restraints were specified for the Calder Hall station. When the commercial nuclear power stations were in the early design stages it was assumed that similar tied bellows would be incorporated in the proposed ducts. In due course a closer examination of the restraint specification and the conditions led one design team to consider hinge-pin units unsafe and another to consider them at least expensive to make safe. In both cases this led to new designs–the tie bar and flexible tongue units.

On a larger scale, or at a higher level, we see a similar situation with the A.G.R. ducts (Fig. 15). The initial layout at the specification stage called for flexible ducts to connect the pressure vessel with the heat exchangers as was general practice to that time. A closer examination, however, when the design got under way showed that flexible ducting for the new conditions–which included space available as well as pressures, temperatures, etc.–was not practicable. Once again there was forced invention to keep the project going–in this case the use of straight co-axial ducts and movable heat-exchangers (see Ref. 5).

A variation of this second cause of design progress is when what is specified is judged to be possible but, being near to its limit, is

deemed to entail a vast effort whilst having little or no future development potential. For commercial reasons there is again forced invention, with a view to providing a cheaper immediate alternative or, for the same development costs, a design with a better future potential.

Conclusion

In this paper an attempt has been made to give a generalised model of the design process in engineering and to discuss why this model takes this particular form.

It has to be recognised that this is tantamount to the description of a natural phenomenon and is not an attempt to find some easy method.

The general steps in design, summarised in Fig. 16, will be passed through inevitably by any designer, professional or amateur, providing he persists, though the results may differ vastly in form and quality and may be obtained elegantly or clumsily in one cycle or more. The generalised model applies equally well to good, bad or indifferent design. Whether the end result is produced efficiently and cheaply in relation to its quality is a function of the quality of thinking and the amount of knowledge which can be brought to bear.

Whilst engineering design is creative in one way or another at all levels and is considered to be a process of synthesis, the words "creative" and particularly "synthesis" should not be interpreted in their dictionary senses. No design exists in complete isolation from other designs, neither, except in unusual circumstances, are designs built upwards by adding together separate elements. Every design must start with a complete idea, however indefinitely conceived, and this is successively broken down into smaller parts which receive greater attention. The definition of the whole is intimately bound up with the definition of all its constituent parts. Initial ideas, whether they relate to the whole design or minor parts of it, will be based upon the individual Designer's knowledge of comparable precedents—the comparability being greater or lesser depending upon the circumstances. Any engineering design is continually being technically assessed and reassessed from the stage when it is but an idea right through to the production drawings—and beyond into tests and operational service. Throughout mathematical, analogous or "equivalent" but simplified models are invoked for purposes of argument (calculations being simply a numerical form of argument) since the reality is always too complex to grasp, and the Designer's task throughout is to judge the probable degree of similarity between the behaviour of these abstractions and that of real material things—which he can only do by having a knowledge of the behaviour of comparable arrangements of material parts.

If any design is more than a reasonable extrapolation of what actually exists in hardware, is tested and proven, then the Designer can never be reasonably certain that something of importance has not been overlooked, or over- or under-estimated. He then has no option but to advance the design through tests and/or prototypes.

This leads to engineering design being essentially a continuous process based on the development, to a greater or lesser degree, of proven precedents, since this is the most efficient way to exploit knowledge and experience, and it only becomes a synthesis of more elementary

elements in the limit when the following of precedents of one kind or another is judged technically or commercially inadequate.

Creative effort, i.e., invention, requires brainpower and thinking time; usually it also requires extensive research development and testing to realise a commercially acceptable design. Efficient design demands that such new design entities should be exploited through successive development so far as is technically and commercially practicable. The substitution of something new for something which is still quite adequate is under-exploitation of the previous design. This is a wastage of creative talent though it may, of course, have to be balanced against other factors.

(1) The Design to the person uninvolved is generally a knowledge of how it works in principle, how it looks or otherwise behaves.

(2) The Design to the production engineer, etc., is the complete definition of the product as expressed in the drawings, lists, specifications and other instructions, resulting from the design process.

(3) The Design to the engineering designer is ultimately the knowledge of all the steps, decisions, calculations, theories, arguments, and so on, which have led to the design taking its particular form, together with a knowledge of its performance and operational characteristics. This understanding allows him to use the design as a precedent for other designs, and then to assess the effort required, the changes that can or should be made and so on.

The above conclusions are tantamount to a summary of an observed activity and they are not recommendations for improving design, etc. The aim of research is to collect factual material and to arrange this in such a way that it makes an ordered whole as opposed to a mass of comparatively unrelated matters. The order thus arrived at is then made meaningful by explaining it in more elementary terms. In the long run the "picture" arrived at, if accepted, can be used as an intermediary to argue policies from stated aims.

Whilst the author would like to record his more general conclusions, this will not be done in this context, since these depend upon discussing initially the fundamental aims of, say, industry, training and education with respect to engineering design.

There is, however, one important general conclusion resulting from this research which is suitable for inclusion; one which is obscured when simple non-critical designs are examined, but which becomes most apparent when investigating designs extended towards their limits.

Engineering design starts—in the form of precedents—and ends—in the form of the proven design—in material things. Irrespective of the intermediate stages, therefore, engineering design is essentially concerned with things and their behaviour in a multitude of circumstances. Whilst all kinds of devices may be used for purposes of argument, to what extent some mathematical, symbolical or analogous model (or even a real scaled model) accords with the behaviour of real material arrangements depends upon the Designer's knowledge of the behaviour of comparable material arrangements and not on the latter generalised into some other abstraction. Consequently the Designer must from the earliest stages of his training be in contact with real material design entities—in their manu-

facture, assembly, testing and operational service—so that he can observe, measure and test their behaviour under various conditions and compare this with his predictions of their behaviour. (Later, he may well, at times, be able to manage with written, graphical or tabulated results compiled by others.) Bringing up prospective designers entirely through work on the drawing board and theoretical studies is, therefore, fundamentally wrong; it is similar to suggesting that physicists need only a theoretical education and need carry out no experimental work as the behaviour of the material world is readily predictable from fundamental theory.

Practical work in most design courses in both colleges and industry is generally confined to simple tests on materials and a study of production processes. The lack of intimate contact with real design entities and the personal observation of such things as noise, vibration, friction, backlash, wear, fits, etc., and their effects on the behaviour of mechanical devices in the widest sense as compared with theoretical performance would seem to be one of the most serious omissions in contemporary training.

Likewise within industry, confining designers and draughtsmen to continual work on the drawing board—as has often been the practice—without the opportunity of seeing how their design work fared in the manufactured product, is the very negation of engineering design which, almost by definition, is continual improvement based upon what the Designer learns from tests and operational service.

A further general conclusion to note is that The Design as expressed in definition (3) above cannot be deduced from The Design in the sense of definition (2). It is quite impossible to reconstruct all the stages of a design, the decisions made, the order of tackling the parts, the form of the calculations and so on, simply by reference to the final drawings, or the resulting hardware. For instance, an examination of Fig. 11 alone gives no clue as to how a similar specification with different figures for end load, bending moment, etc., could be dealt with—or even if it is possible using the frusto-conical principle. Consequently, filing away drawings is not retaining design knowledge. In many instances The Design, in the sense of definition (3), exists only in the Designer's head. Without the retention of extensive files recording the evolution of each design, engineering design—other than matters capable of generalisation—can only be transmitted from person to person, usually by a newcomer running through a complete design cycle in the company of a more experienced person. It is the deep understanding thereby gained which allows design to proceed without continually taking the form of expensive development.

On the other hand a lot could probably be done to retain design knowledge within industry by systematic documentation during the design process. Newcomers and replacements would then be in a better position to understand why a design at any particular stage is as it is; such documentation would also be of very great help if the design were to be used as a precedent for satisfying a similar specification.

Acknowledgements

In collecting the material for this paper, the author has received very willing and helpful cooperation from many quarters, although it is to be noted that the views expressed

are entirely those of the author and are not necessarily endorsed by the Companies concerned.

Very great thanks are due to the Directors and Staff of Messrs. Richardsons, Westgarth and Company Ltd., Wallsend, Northumberland, and of Atomic Power Constructions Ltd., and to the Central Electricity Generating Board for permission to publish this paper.

Thanks are also due to the authors of papers quoted, and to Messrs. C. A. Parsons & Co. Ltd., Associated Electrical Industries (Heavy Plant Division) Ltd., Messrs. Babcock & Wilcox Ltd., A. P. Newall & Co. Ltd., Teddington Aircraft Control (Bellows Division) Ltd., and Engineering Appliances Ltd. (for Industrie-Werke Karlsruhe) for providing copies of photographs and much background information.

The author would also like to thank Mr. D. L. Marples for making available research material not used in his paper (Ref. 5), and in particular Dr. A. Frankel, Mr. J. A. Lorett, Mr. G. N. Doyle, Mr. J. J. Haftke and Mr. V. Westerman for their personal help and interest.

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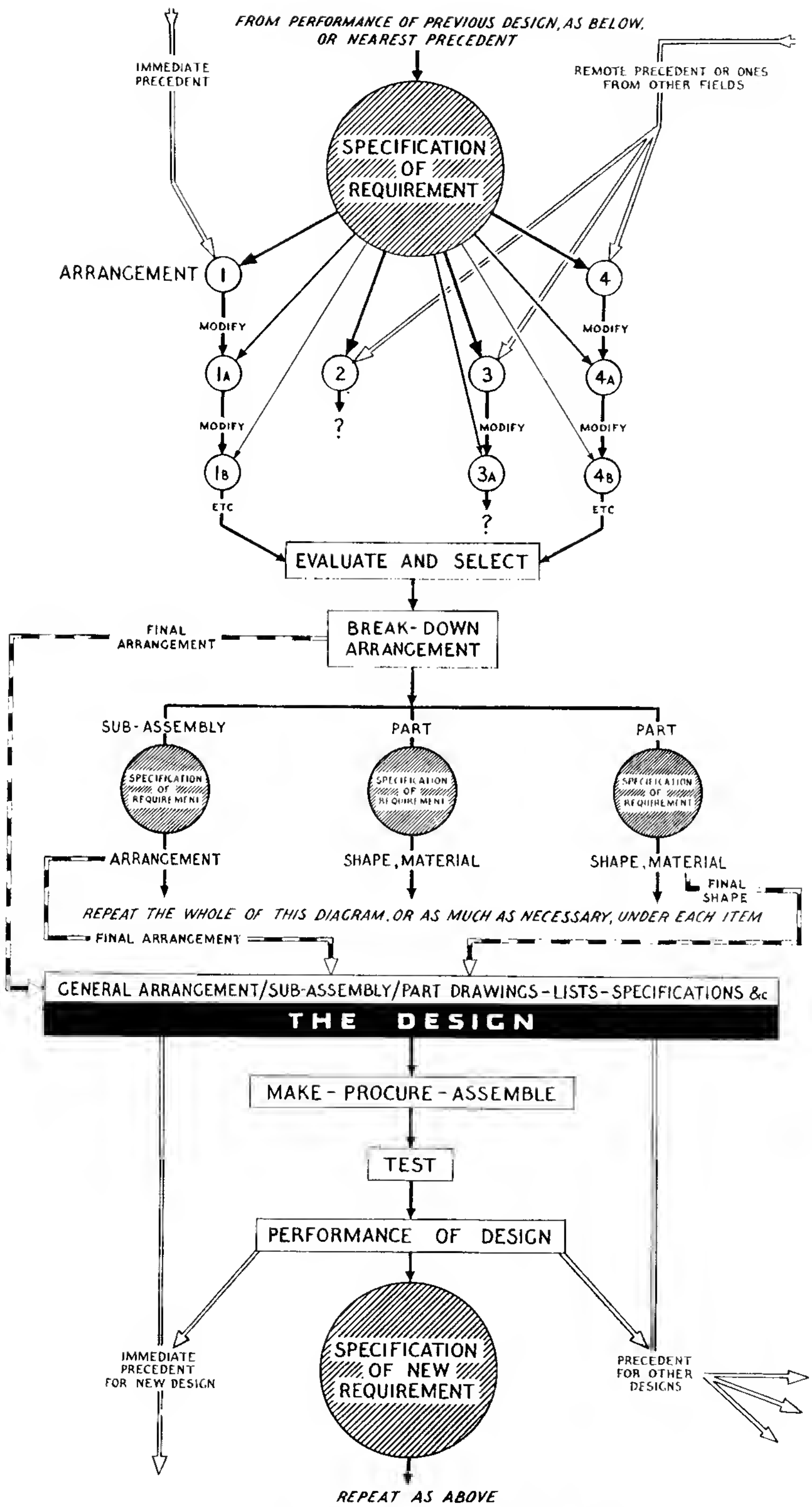

Fig. 16. Generalised Model of Engineering Design.

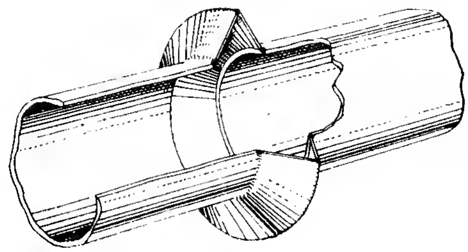

Fig. 17. An early flexible pipe joint using sheet metal frusto-cones.

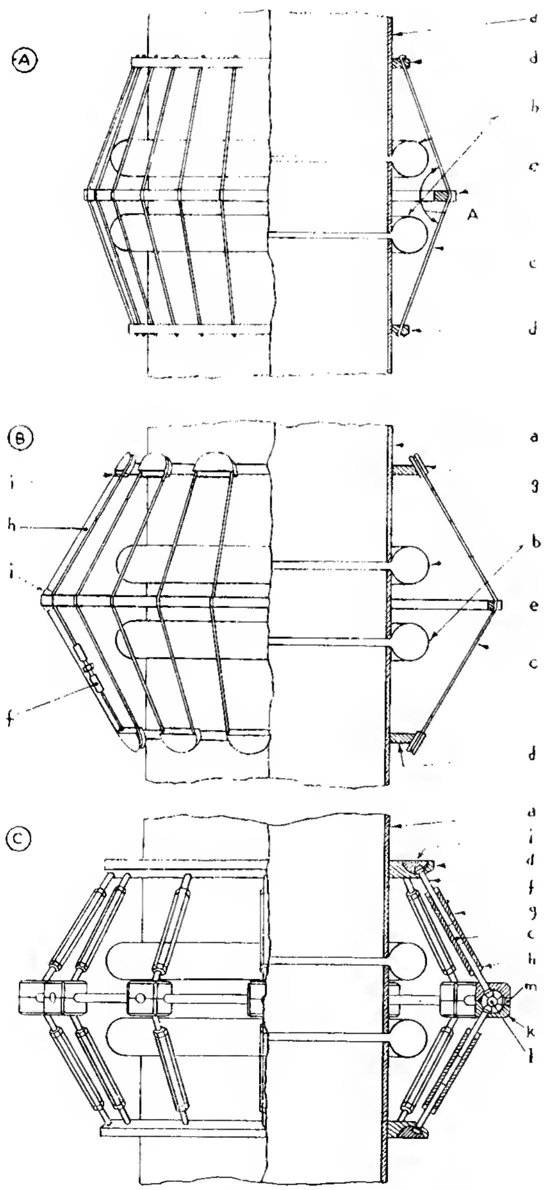

Fig. 18. Another use of the frusto-conical principle in duct joints (See Ref. 8).